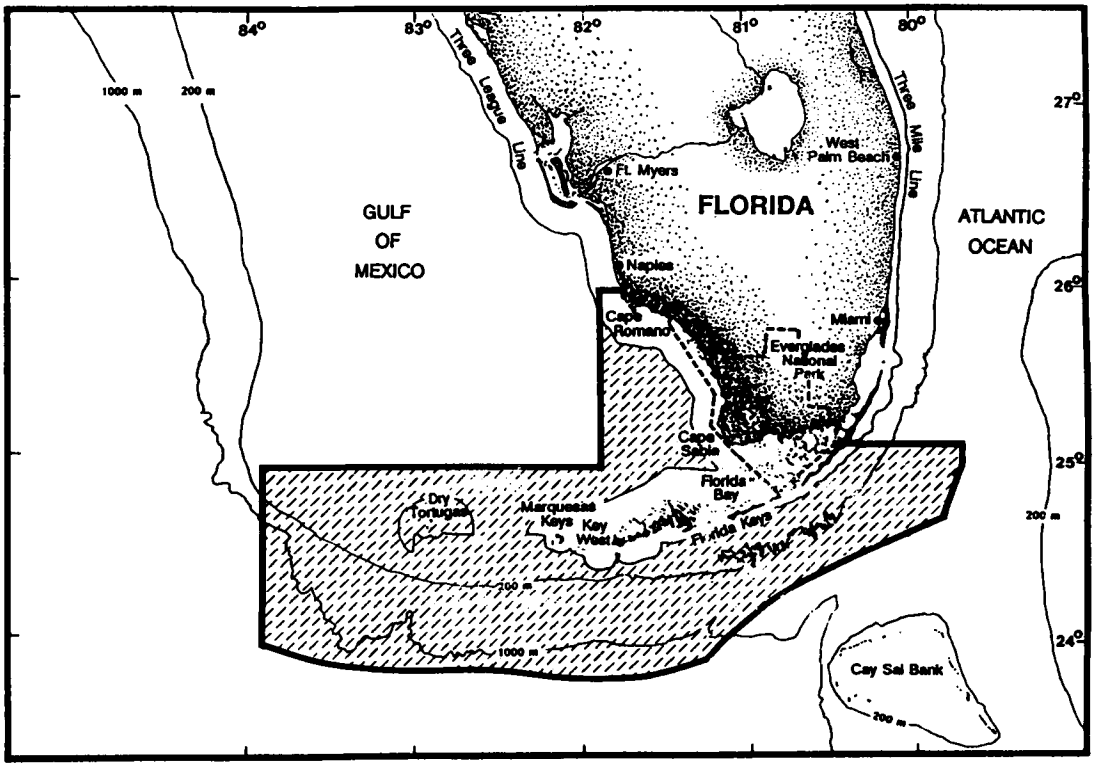
OCS Study
MMS 90-0019

Synthesis of Available Biological, Geological, Chemical, Socioeconomic, and Cultural Resource Information for the South Florida Area



Prepared by

Continental Shelf Associates, Inc.

Contract No. 14-12-0001-30417

Prepared for

U.S. Department of the Interior
Minerals Management Service
Atlantic OCS Region

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MMS 90-0019

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May 1990

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Continental Shelf Associates, Inc.
759 Parkway Street
Jupiter, Florida 33477
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U.S. Department of the Interior
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Atlantic OCS Region

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Dr. Gilbert L. Voss, a Quality Review Board member at the beginning of the program, passed away in early 1989. He provided access to unpublished data and documents, as well as forthright, constructive criticism of the technical approach at the First Coordination Meeting in November 1988.

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Dr. Ronald J. Larson also provided technical and editorial comments on portions of the draft report.

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CHAPTER 1
INTRODUCTION

Neal W. Phillips

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BACKGROUND

Coastal South Florida is a region of diverse and striking natural beauty. Within a radius of a hundred miles or so lies a unique combination of tropical and subtropical habitats, from the Everglades "river of grass" to the corals of the Florida Reef Tract, from the lush seagrass meadows of Florida Bay to the dense mangrove forests of the Ten Thousand Islands. These habitats support an abundance of fish and wildlife; sustain valuable commercial and recreational fisheries; and attract anglers, divers, naturalists, and other tourists from all over the world. The region includes over 60 sites of special concern, including State and National parks, aquatic preserves, wildlife refuges, and marine and estuarine sanctuaries.

South Florida is also an oil and gas producing region. In 1943, Humble Oil and Refining Company discovered oil near the Collier County railroad water stop of Sunniland (Montgomery 1987). Since then, 14 producing fields have been discovered along a feature now known as the Sunniland Trend (**Figure 1.1**). South Florida fields have yielded 92 million barrels of oil and 8 billion cubic feet of natural gas through 1988 (D. Curry, pers. comm. 1989, Florida Bureau of Geology). By comparison with major oil producing states such as Alaska and Texas, these figures are modest; in 1988, Florida ranked 19th nationally and accounted for about 0.26% of total domestic oil production (Energy Information Administration 1989).

Geologically, the Sunniland Formation is part of the South Florida Basin, which encompasses the mainland of South Florida, as well as the Florida Keys, Florida Bay, and the Southwest Florida shelf (**Figure 1.1**). The true hydrocarbon potential of the basin is uncertain because only a few hundred wells have been drilled to evaluate an area of over 200,000 km^2 (Montgomery 1987). Most experts believe that several formations other than the Sunniland hold potential for commercially significant finds (Amato et al. 1986; Faulkner and Applegate 1986; Applegate 1987; Montgomery 1987). Offshore portions of the basin are believed to hold greater potential because the sedimentary environment is more geochemically mature (Faulkner and Applegate 1986).

Because of increasing industry interest in South Florida, the Minerals Management Service (MMS)[1] recently proposed to lease Federal offshore tracts in the Straits of Florida, near the Florida Keys. A lease sale in this area was included in the Proposed 5-Year Outer Continental Shelf Oil and Gas Leasing Program (hereafter referred to as the 5-Year Program) issued in July 1987 (MMS 1987). However, in response to opposition from the State of Florida, the Secretary of the Interior deleted the proposed sale from the 5-Year Program in March 1988. At the same time, the Secretary deferred adjacent areas from leasing under two Eastern Gulf of Mexico Planning Area sales that remained in the 5-Year Program. Deletion of the proposed lease sale from the 5-Year Program allowed additional time to gather and synthesize information about potential environmental and socioeconomic effects of offshore drilling and production.

[1]The MMS is an agency of the U.S. Department of the Interior that leases submerged Federal lands and supervises oil and gas exploration, development, and production. Prior to 1982, these functions were the responsibility of the Bureau of Land Management.

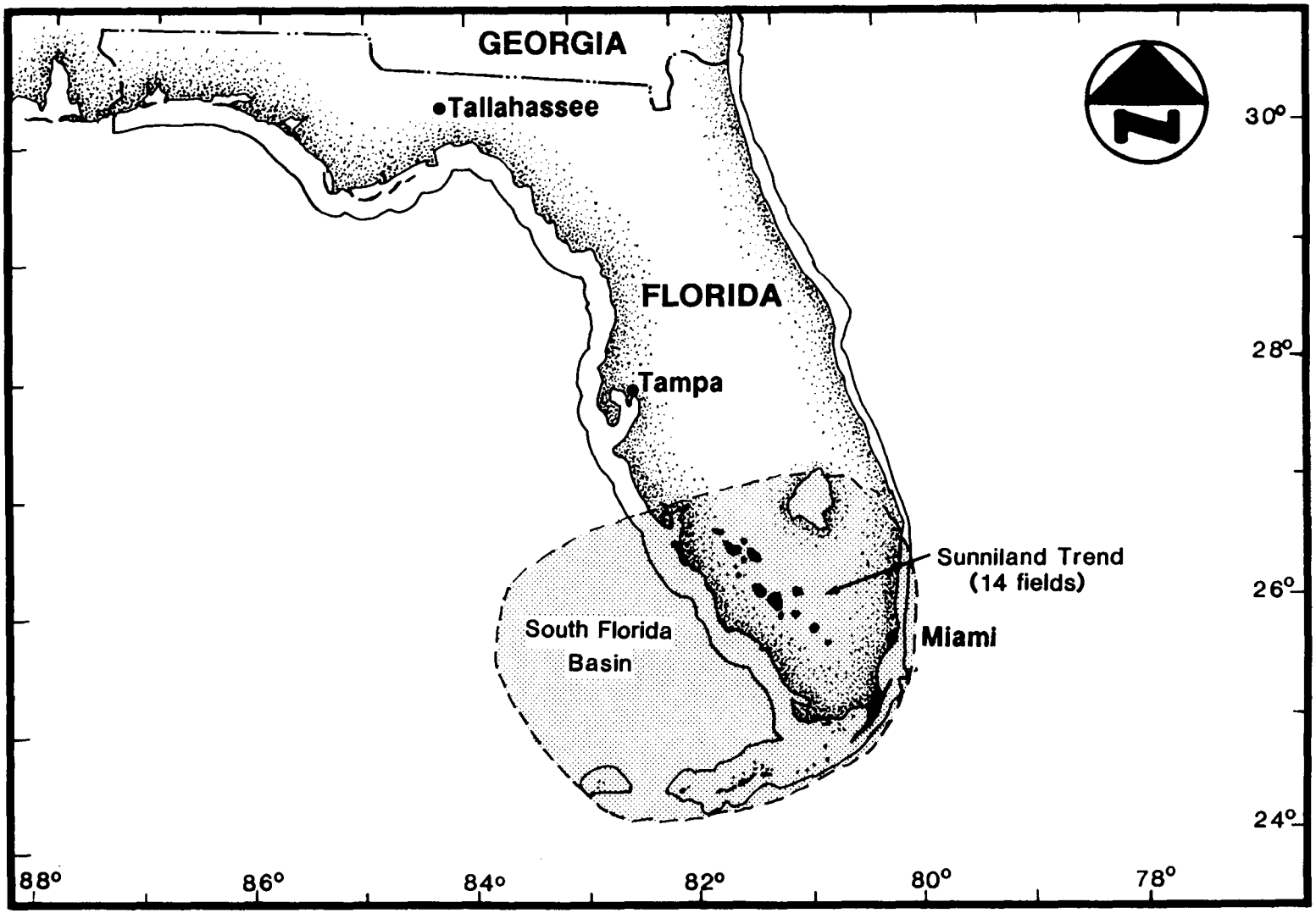

Figure 1.1. Location of South Florida Basin and Sunniland Trend (From: Montgomery 1987).

Offshore leasing in South Florida is controversial because of the environmental, economic, and aesthetic value of the region's coastal and nearshore habitats. The possibility of a major oil spill has received the most public attention, particularly since the March 1989 *Exxon Valdez* spill in Prince William Sound, Alaska. Other potential environmental and socioeconomic effects associated with routine offshore exploration and production have received less attention, but must also be weighed in future decisions about leasing in the area.

OBJECTIVES

Numerous environmental and socioeconomic studies have been conducted in South Florida by various Federal and State agencies, university researchers, private organizations, and individuals (see **Appendix A** for a brief listing of studies conducted by the U.S. Department of the Interior). The MMS sponsored this study to summarize the available information and evaluate potential effects of offshore oil and gas exploration and development. The synthesis will help Federal and State policy makers to reach informed decisions about future lease offerings and environmental restrictions on offshore oil and gas operations.

The specific objectives of the study were (1) to review and synthesize geological, chemical, biological, cultural resource, and socioeconomic information for the study area; (2) to evaluate potential effects of offshore oil and gas exploration and development; and (3) to recommend mitigation measures and evaluate future research needs.

STUDY AREA

The study area includes the Straits of Florida, the Florida Keys, the Dry Tortugas, Florida Bay (including portions of Everglades National Park), the Ten Thousand Islands region, and part of the Southwest Florida continental shelf (**Figure 1.2**). The synthesis focuses on the area between the mean high water mark and the 200-m isobath. Pertinent information from surrounding areas (e.g., U.S. Exclusive Economic Zone) is included as appropriate.

From a leasing standpoint, the study area consists of two parts (**Figure 1.2**):

- The Straits of Florida Planning Area south of 25°07'N. This area was originally scheduled for a lease sale in 1991 under the 5-Year Program (MMS 1987). However, the Secretary of the Interior deleted the sale from the 5-Year Program in March 1988 after negotiations with the State of Florida. The MMS had already stated that the northern part of the Straits of Florida Planning Area would be deferred if a lease sale were held.

- The southern portion (expansion area) of the Eastern Gulf of Mexico Planning Area. Under the 5-Year Program, this area could have been offered for lease in two sales scheduled for 1988 and 1991. The area was deferred from leasing in March 1988 under the agreement between the Secretary of the Interior and the State of Florida.

Additional information on the leasing history and status of South Florida is presented in **Chapter 12.**

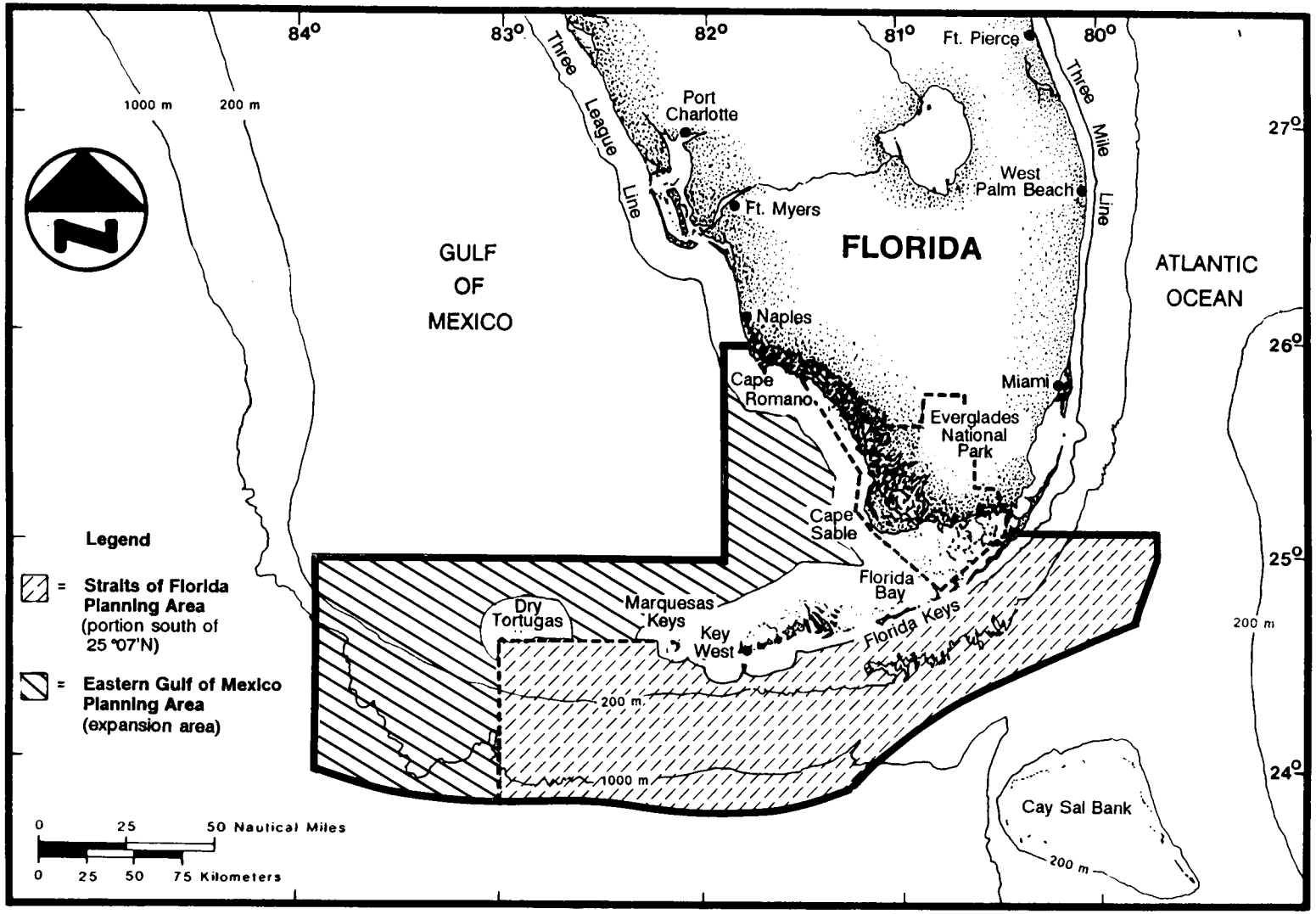

Figure 1.2. Study area.

METHODS AND REPORT ORGANIZATION

Information on various environmental and socioeconomic topics was synthesized by experts in each discipline. Information was collected through computer searches, telephone contacts, and library visits (**Appendix A**), and authors were supplied with literature according to their individual needs.

The manuscript is organized by discipline. **Chapter 2** (Geologic Setting) and **Chapter 3** (Environmental Chemistry) describe the abiotic environment.[2] **Chapters 4** through **9** discuss biological topics: Coastal and Nearshore Communities; Offshore Benthic Communities; Plankton; Fish Communities and Fisheries Biology; Marine Mammals and Sea Turtles; and Coastal and Marine Birds. The next two chapters focus on the human environment, past (**Chapter 10**, Submerged Cultural Resources) and present (**Chapter 11**, Socioeconomics). **Chapters 12** through **16** are devoted to evaluating potential effects of offshore oil and gas exploration and development. Finally, **Chapter 17** (Conclusions and Recommendations) summarizes major findings and presents recommendations for mitigation measures and further studies.

Each chapter begins with an Introduction and ends with a Conclusions section that highlights significant findings, identifies gaps in knowledge and understanding, and describes further studies that could help to fill those gaps. In the descriptive chapters (**2** through **11**), the Conclusions sections focus on basic knowledge rather than information needed for management decisions. The findings and information needs that are most important for management decisions are drawn together in **Chapter 17** (Conclusions and Recommendations).

REFERENCES CITED

Amato, R. V., W. E. Sweet, G. M. Edson, C. J. O'Hara, D. M. Clark, and G. Pickens. 1986. *Regional geology and petroleum potential of the Straits of Florida Planning Area*. U.S. Department of the Interior, Minerals Management Service. Unpubl. manuscript.

Applegate, A. V. 1987. *The brown dolomite zone of the Lehigh Acres formation (Aptian) in the South Florida Basin--A potentially prolific producing horizon offshore*. Fla. Bur. Geol. Info. Circ. No. 104, Pt. II. Tallahassee.

Energy Information Administration. 1989. *Petroleum supply annual 1988, Vol. 1*. Washington, DC: U.S. Government Printing Office.

Faulkner, B. M., and A. V. Applegate. 1986. Hydrocarbon exploration evaluation of the Pulley Ridge area, offshore South Florida Basin. *Trans. Gulf Coast Assoc. Geol. Soc.* 36:83-95.

Minerals Management Service. 1987. *Proposed 5-year outer continental shelf oil and gas leasing program, mid-1987 to mid-1992. Final environmental impact statement*. OCS EIS/EA MMS 86-0127. Washington, DC: U.S. Government Printing Office.

Montgomery, S. L. 1987. Success and sensibility in South Florida. *Pet. Front.* 4(3):1-52.

[2] A physical oceanography chapter is not included because that information is being synthesized under a separate MMS contract. Brief discussions of physical oceanography are presented in **Chapters 2** and **6**.

CHAPTER 2
GEOLOGIC SETTING

Gregg R. Brooks

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INTRODUCTION

South Florida is part of a vast, gently sloping, carbonate platform. It consists of a variety of environments ranging from the reef-rimmed margin seaward of the Florida Keys, through the relatively low-energy, protected Florida Bay environment, to the more open Southwest Florida margin. Modern sediment types reflect these different environments, ranging from almost pure carbonate in the Florida Keys/Reef Tract and Florida Bay, to essentially pure quartz sands along the inner Southwest Florida shelf, to almost pure carbonate again on the outer Southwest Florida shelf and slope.

For discussion purposes, the South Florida study area will be divided into three units: (1) the Florida Keys and Reef Tract; (2) Florida Bay; and (3) the Southwest Florida continental margin, including the shelf and upper slope (**Figure 2.1**). Each represents a distinct environment from a geologic perspective and will be discussed separately. The discussion will focus on the region extending from the coastline to a depth of approximately 200 m, which corresponds generally to the outer continental shelf to upper continental slope zone. The area known as the Straits of Florida will not be dealt with separately, but will be incorporated into other discussions.

The review begins with a brief section on the general geologic history and physical oceanographic setting of the area. Physical oceanography is included because in many cases physical oceanographic processes influence the geologic development and modern configuration of the platform. Each of the three units recognized above is then discussed individually in terms of recent geologic development and modern configuration, including patterns, processes, and controls influencing modern distribution. Discussions are based upon the extent of knowledge of each unit and therefore vary somewhat in content. The review ends with a discussion of petroleum geology and geohazards, followed by an evaluation of data gaps and further research needs.

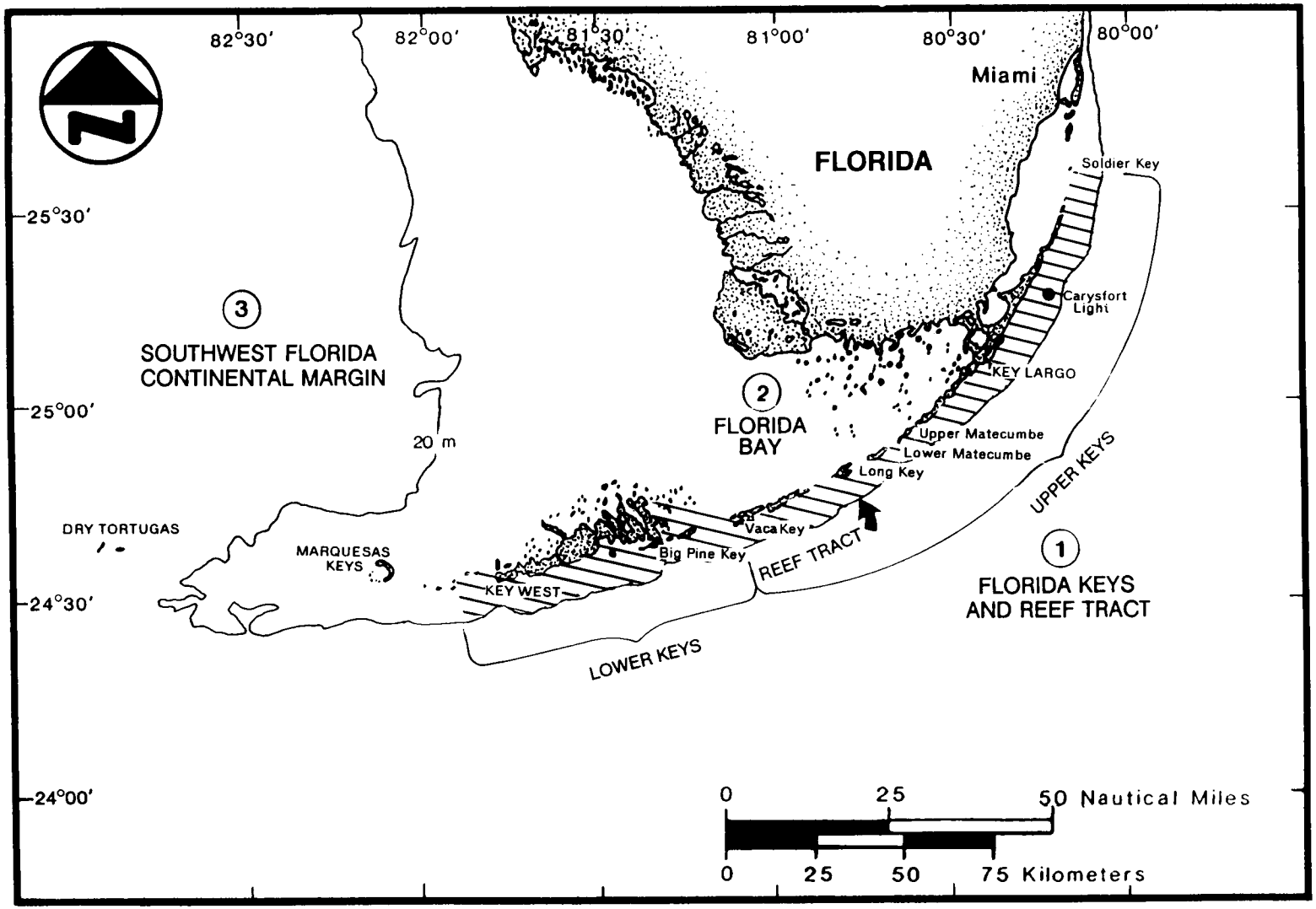

Figure 2.1. Geomorphic units of the study area: (1) Florida Keys and Reef Tract, (2) Florida Bay, and (3) Southwest Florida continental margin (Adapted from: Hoffmeister 1974).

REGIONAL SETTING

Geologic History

South Florida is the southern extent of the vast Florida platform, a southward thickening wedge of Mesozoic and Cenozoic carbonates and evaporites that reaches a thickness of at least 5,000 m in the South Florida Basin (**Figure 1.1**) (Pyle et al. 1974; Montgomery 1987). The geologic basement beneath South Florida consists of a patchwork of igneous, metamorphic, and sedimentary rocks possibly ranging in age from 89 million years (Late Cretaceous) to more than 500 million years (Cambrian or possibly pre-Cambrian) (Pyle et al. 1974). This patchwork has characteristics of both oceanic and continental crust. Therefore, it probably represents "transitional" crust (Krivoy and Pyle 1972; Martin 1976; Schlager et al. 1984) because it occupies a broad, transform-fault boundary between the northwest-trending Bahamas and Campeche fracture zones linking Atlantic and Gulf of Mexico spreading centers (Klitgord et al. 1984). The South Florida Basin, which occupies approximately 200,000 km^2 encompassing almost the entire South Florida peninsula, was probably formed by block faulting associated with these fracture zones when they were active during the Triassic-Jurassic period (Klitgord et al. 1984). Thus, the South Florida Basin is a very old, structurally controlled feature.

Since its formation in the Mesozoic, the South Florida Basin has remained a largely undisturbed site of continuous carbonate-evaporite deposition. **Figure 2.2** shows a generalized stratigraphic section of the South Florida Basin from the Triassic-Jurassic to the present. Overlying basement is the Late Jurassic-Early Cretaceous Wood River Formation, consisting of a basal section of thin shales, fine- to coarse-grained arkosic sandstone, and red calcareous sandstone. Overlying these rocks are occasional salt stringers and a thick sequence of anhydrite and microcrystalline brown dolomite, with minor amounts of micritic limestone. The Wood River Formation averages about 900 m in thickness and is interpreted to have formed during a marine transgression (Applegate and Lloyd 1987; Montgomery 1987).

Overlying the Wood River Formation are the Bone Island and Pumpkin Bay Formations. Both are similar to the upper Wood River Formation, consisting of limestone, dolomite, and anhydrite, but with a somewhat greater abundance of micritic and oolitic limestone. Average thicknesses for the Bone Island and Pumpkin Bay Formations are approximately 600 m and 365 m, respectively (Applegate and Lloyd 1987).

Overlying the Pumpkin Bay Formation is the Lehigh Acres Formation, which consists of three members. The lowermost is the West Felda Shale, which is interpreted to represent a brief transgressive period. Overlying this shale is the Twelve Mile Member, consisting of micritic, pelletal and oolitic limestone, brown dolomite, and argillaceous limestone. Above the Twelve Mile Member is the Able Member, consisting of anhydrite interbedded with micritic and argillaceous limestones. Collectively, all three units of the Lehigh Acres Formation average 200 m in thickness (Applegate and Lloyd 1987; Montgomery 1987).

The Early Cretaceous Punta Gorda Formation directly overlies the Able Member of the Lehigh Acres. The major portion of the Punta Gorda is anhydrite overlain by micritic limestone, dense dolomite, and thin calcareous shale. The unit is interpreted to have developed in a sabkha-type tidal flat environment. It averages approximately 180 m in thickness (Applegate and Lloyd 1987; Montgomery 1987).

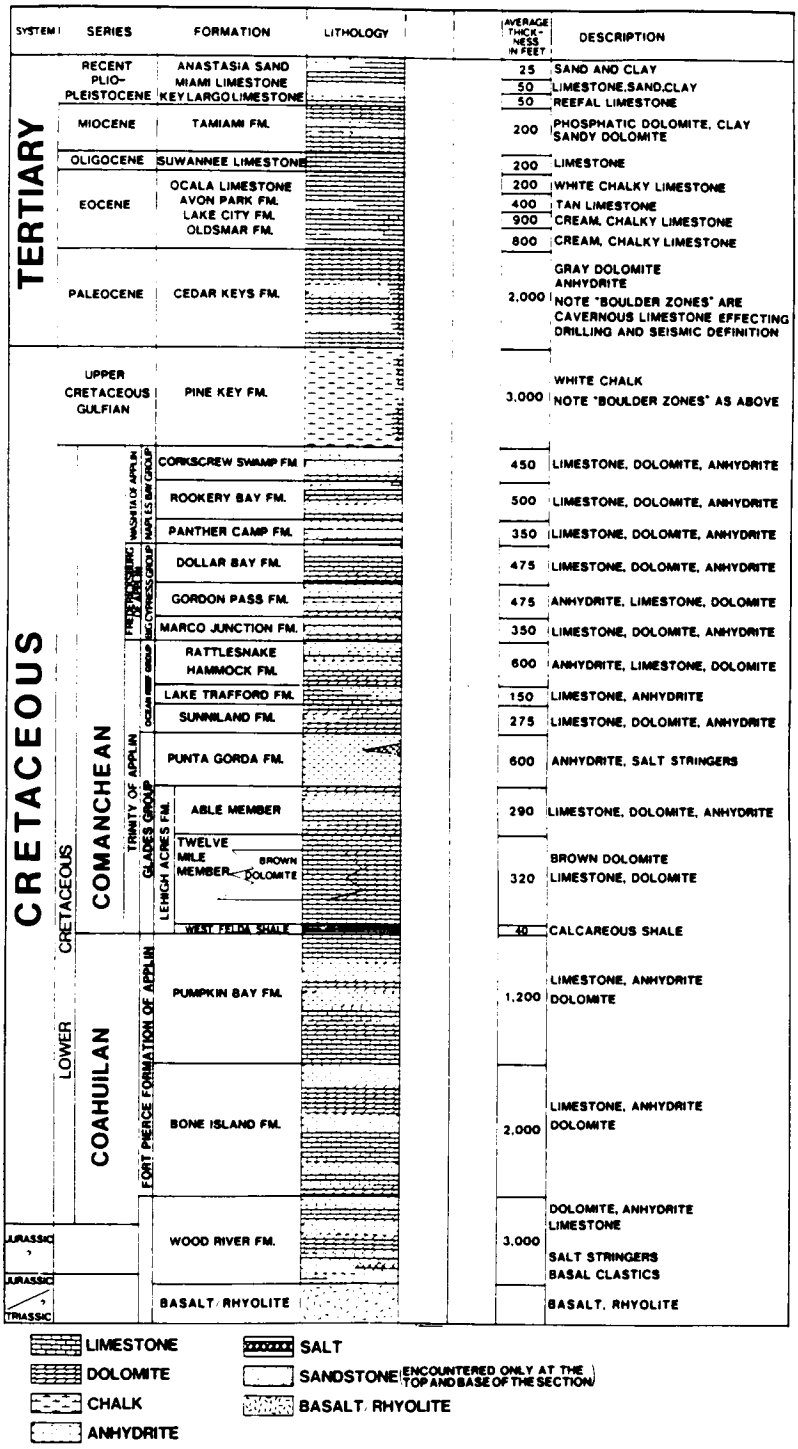

Figure 2.2. General stratigraphic sections of the South Florida Basin (Adapted from: Faulkner and Applegate 1986).

The overlying Sunniland Formation has been the most intensively studied unit of the South Florida Basin because it is the only petroleum-producing interval identified to date. Most researchers agree that it formed in a warm, shallow, marine-shelf setting during the Early Cretaceous (Montgomery 1987). The Sunniland Formation generally consists of a combination of limestone, dolomite, and anhydrite, and averages 85 m in thickness. The producing zones consist of grainstone mounds interpreted to represent either *in situ* fragmented remains of localized reef buildups, or fragmented and reworked debris from rudistid reefs (Applegate and Lloyd 1987; Montgomery 1987). Alternatively, the mounds may have originated in a tidal mudflat setting similar to the modern Florida Bay environment (Mitchell-Tapping 1986).

Immediately overlying the Sunniland Formation and acting as a caprock is the Lake Trafford Anhydrite. The unit consists of both marine anhydrite and anhydrite interbedded with argillaceous limestone, interpreted to have formed during a continued sea level regression. Average thickness is approximately 45 m (Applegate and Lloyd 1987; Montgomery 1987).

Above the Lake Trafford Anhydrite is a 900-m-thick section of interbedded limestone, dolomite, and anhydrite, representing the remainder of the Early Cretaceous. From oldest to youngest, individual units include the Rattlesnake Hammock Formation, Marco Junction Formation, Gordon Pass Formation, Dollar Bay Formation, Panther Camp Formation, Rookery Bay Formation, and Corkscrew Swamp Formation (**Figure 2.2**). During the Early Cretaceous, when these units were deposited, South Florida remained a shallow, partly starved basin separated from the open ocean by a continuous, shelf-edge reef trend (Applegate and Lloyd 1987; Montgomery 1987). Overlying these units is the Late Cretaceous Pine Key Formation, which consists of a soft, chalky carbonate and contains "boulder zones" or zones of large caverns. It averages 900 m in thickness and is interpreted to have formed during a major sea level transgression (Applegate and Lloyd 1987; Montgomery 1987).

The Paleocene Epoch in South Florida is represented by the 600-m-thick Cedar Keys Formation, which consists of dolomite and anhydrite; the Eocene by the Oldsmar, Lake City, Avon Park, and Ocala Formations (limestones), which collectively average 760 m in thickness; the Oligocene by the 60-m-thick Suwannee Limestone; and the Miocene by the 60-m-thick Tamiami Formation, which consists of clay-to-sand-rich phosphatic dolomite. Pleistocene and Recent units will be discussed in subsequent sections. In general, South Florida during the Cenozoic seems to have been a stable carbonate platform undergoing continual subsidence and influenced by multiple sea level fluctuations (Applegate and Lloyd 1987; Montgomery 1987).

Physical Oceanography

The physical environment of the Straits of Florida is dominated by the Florida Current, a surface current that flows east and then north, linking the Loop Current of the Gulf of Mexico with the Gulf Stream (**Figure 2.3**). Surface velocities average 100 cm/s, but reach up to 250 cm/s in the core of the flow (Richardson et al. 1969). Average downstream velocities tend to increase in the northern Straits, presumably as a result of the decreased cross-sectional area of the channel (Lee 1989). A countercurrent occurs landward of the Florida Current, west of the Lower Keys (Brooks and Niiler 1975), but has not been reported off Miami (Lee 1989). The origin of the countercurrent is uncertain, but it may represent a cyclonic recirculation of Florida Current water (Brooks and Niiler 1975). A deep countercurrent has also been identified, with velocities reaching 90 cm/s off Miami (Lee 1989). In the southern Straits, this countercurrent exists at depths ranging from 430 to 600 m or more below sea level (Stewart 1962; Brooks and Niiler 1975). Muddy sediment drifts at the junction between the

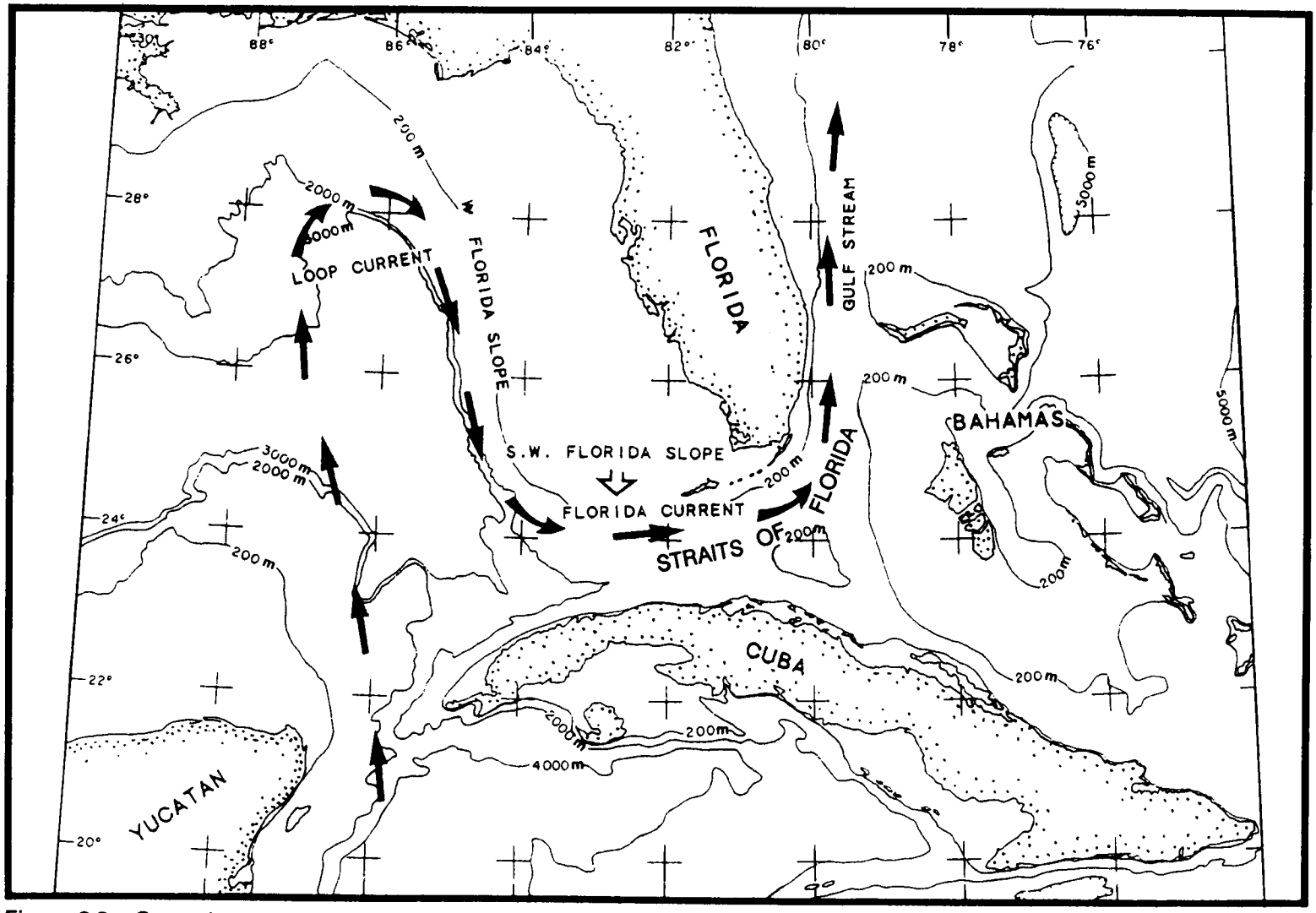

Figure 2.3. General configuration of the Loop Current in the Gulf of Mexico.

southern Straits of Florida and Gulf of Mexico (Brunner 1986) suggest that these deep currents have been capable of transporting relatively large quantities of mud-sized sediments in the recent geologic past. Between 200- and 430-m water depths exists a zone of reversal over which the flow gradually changes direction (Stewart 1962; Brooks and Niiler 1975). Flow velocities are sluggish throughout this entire zone.

The Southwest Florida continental shelf is under the influence of several physical processes that affect surface geology. Currents, tides, and surface waves operating independently and in combination have been shown to significantly influence sediment distribution and the overall geologic configuration of the shelf and upper slope. The Loop Current *per se* rarely intrudes onto the shelf landward of the 100-m isobath, but associated phenomena, such as warm filaments, frequently intrude into the study area (Environmental Science and Engineering, Inc. et al. 1987). Periodic or intermittent intrusion of Loop Current water onto the shelf has been identified as a possible mechanism for the southerly transport of sediments along the outer shelf (Neurauter 1979).

Tides on the Southwest Florida shelf are mixed diurnal/semidiurnal and weakly developed, with ranges of approximately 0.7 m during neap tides and 1.5 m during spring tides (Environmental Science and Engineering, Inc. et al. 1987). Tidal currents are strongest along the inner shelf, where velocities commonly exceed 20 cm/s (Environmental Science and Engineering, Inc. et al. 1987)--sufficient to transport even sand-sized material. In addition, strong reversing tidal currents have been observed as they are funnelled between the shallow carbonate banks (e.g., Marquesas Keys and Dry Tortugas) along the southern shelf-slope break. Shallow-water carbonate sediments deposited on the Southwest Florida slope have, in part, been attributed to transport and eventual deposition by these tidal currents (Milligan 1962; Brooks 1986a).

Surface waves are important from a geological perspective, in that they can erode bottom sediments that ultimately may be transported and deposited elsewhere. Waves on the Southwest Florida shelf are predominantly from the east and northeast from September through February, and from the east and southeast from March through August (Environmental Science and Engineering, Inc. et al. 1987). Mean monthly wave heights range from 0.7 to 1.5 m, with the highest between November and March (Environmental Science and Engineering, Inc. et al. 1987). Based upon wave buoy data, Danek and Lewbel (1986) calculated that surface wave energy in water depths <15 m commonly penetrates to the bottom and resuspends bottom sediments. Surface wave energy becomes less influential with increasing water depth and probably never penetrates to depths >125 m.

The most important physical parameters from a geologic perspective include short-term phenomena (e.g., the passage of hurricanes, tropical storms, and frontal systems) and the intermittent shoreward intrusion of warm filaments associated with the Loop Current. Warm filament intrusions can extend across nearly the entire shelf and can increase the average current velocity by a factor of two for 5 to 10 days (Environmental Science and Engineering, Inc. et al. 1987), thereby increasing the potential for bottom sediment erosion and transport.

Hurricanes, tropical storms, and winter cold fronts can greatly increase bottom current velocities, and consequently, the potential for sediment erosion and transport. Bottom currents during the 1985 Tropical Storm *Bob* showed rapid responses to surface wind stresses landward of the 50-m isobath, and showed an increase in velocity from 5 to 35 cm/s at a water depth of 10 m (Environmental Science and Engineering, Inc. et al. 1987). These high-energy events are probably responsible for the export of cold, dense

water (during winter cold fronts) (Roberts et al. 1982) and off-shelf transport of shelf-derived sediments along the Southwest Florida margin (Brooks 1986a).

The main physical parameters influencing the geology of Florida Bay (**Figures 2.1** and **2.4**) are tides and wind-generated currents. Tidal exchange between Florida Bay and the Atlantic Ocean is limited by the Florida Keys. Similarly, tidal exchange between the Bay and the Gulf of Mexico is confined to the relatively few channels between the large, western mudbanks. Within the bay, circulation is further restricted by the near-surface mudbanks (McCallum and Stockman 1972; Merriam 1989). Notwithstanding, tidal currents in some parts of Florida Bay are an important factor affecting sediment distribution (Roberts et al. 1977). However, major changes usually occur during severe storms, which effectively suspend and redistribute sediments throughout the Florida Bay area (Price 1967; Merriam 1989).

Along the Florida Keys and Reef Tract (**Figures 2.1** and **2.4**), the strong Florida Current does not normally impinge directly on the shallow shelf, but stays immediately seaward of the shelf break. Its direct effect on the distribution of shelf sediments, therefore, is minimal. Currents on the inner shelf margin (just seaward of the Keys) are tidally controlled, and although they reverse in response to ebb and flood, show a slight westward component (Enos 1977). Velocities average 5 to 15 cm/s, but have been reported as high as 34 cm/s. Where tidal flow is channeled by the Florida Keys, velocities can be much greater, reaching up to 130 cm/s (Enos 1977). Currents on most parts of the outer shelf margin (just landward of the Reef Tract) correlate closely with wind direction and velocity. Prevailing winds are the southeast trade winds during summer and northeast storm-generated winds during winter. Current measurements and direct observations suggest that wind-driven currents are the most effective processes influencing sediment transport on the margin (Enos 1977).

FLORIDA KEYS AND REEF TRACT

The Florida Keys are a narrow chain of small islands extending from the vicinity of Miami on the north to Key West on the southwest (**Figures 2.1** and **2.4**). Totalling approximately 250 km (135 nmi) in length, they form a gentle arc, with the convex side bounded by the Atlantic Ocean and the concave side by Florida Bay and the Gulf of Mexico (Hoffmeister and Multer 1968). Seaward of the Keys lies the Florida Reef Tract, a series of living coral reefs extending for roughly 96 km (52 nmi) along the present shelf edge at the margin of the Straits of Florida (Marszalek et al. 1977). The origin, development, and modern configuration of the Florida Keys and Reef Tract are fairly well documented, having been the subject of numerous investigations (e.g., Hoffmeister and Multer 1968; Ginsburg 1972; Hoffmeister 1974; Enos and Perkins 1977; Multer 1977; Shinn et al. 1977, 1981, 1989; Shinn 1988).

Geologic Development

Miami and Key West occupy opposite ends of an ancient Reef Tract that flourished during the Late Pleistocene sea level high-stand of approximately 125,000 years ago (Shinn 1988). Most of the Florida Keys is relatively low-lying, projecting <1 to 2 m above sea level, but reaching an elevation of over 5 m on Windley Key in the Upper Keys (Hoffmeister 1974). The surfaces of most of the Keys are flat, with the exception of the Upper Keys, which generally are a meter or two higher along their central axes and slope gently toward the ocean and Florida Bay sides (Hoffmeister 1974).

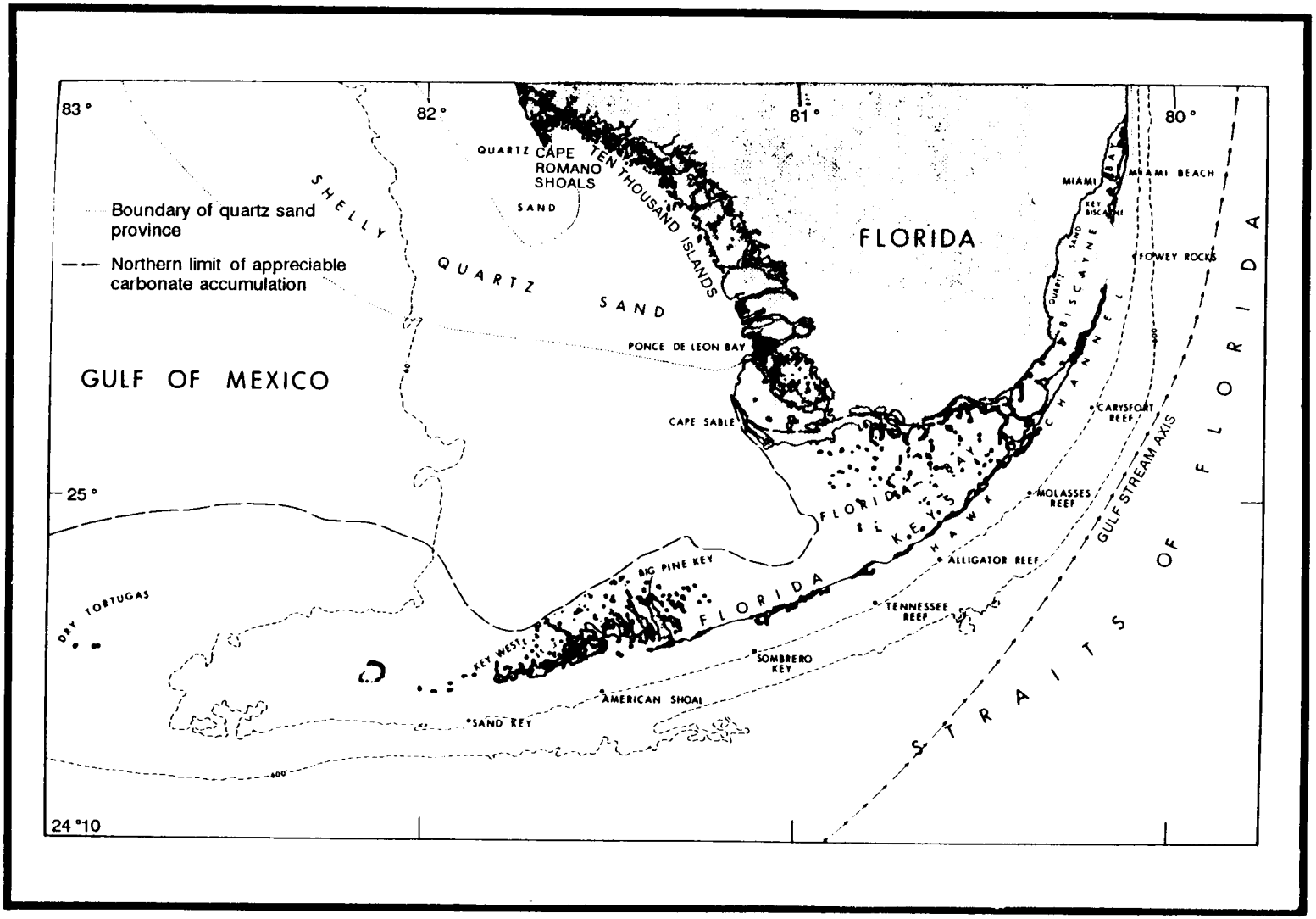

Figure 2.4. Location, general configuration, and major sedimentological provinces of the Florida Keys/Reef Tract, Florida Bay, and portions of the Southwest Florida continental margin (From: Enos and Perkins 1977).

The Keys can be divided naturally into two groups: the Upper Keys and the Lower Keys (**Figure 2.1**). The most obvious and easily recognized distinction is that the Upper Keys are oriented with their long axes along the line of the arc, in a southwesterly direction. The Lower Keys, on the other hand, are oriented with their long axes at almost right angles to the arc, and are separated from each other by narrow channels that run in a northwest-southeast direction (Hoffmeister and Multer 1968; Hoffmeister 1974).

The modern configuration of the Florida Keys, as well as their natural division into two groups, can be traced back to their Late Pleistocene development. Although the entire length of the Keys is underlain by limestone, the foundation for the Upper Keys is an ancient coral reef rock known as the Key Largo Limestone, whereas the foundation for the Lower Keys (and Southeast Florida mainland) consists of the oolite facies of the Miami Limestone (Hoffmeister and Multer 1968). The two limestones were formed by distinctly different processes.

The Key Largo Limestone extends on the surface approximately 180 km (100 nmi) from Soldier Key (just south of Key Biscayne) on the north through the westernmost of the Newfound Harbor Keys (just south of Big Pine Key), where it terminates at Newfound Harbor Channel (Hoffmeister and Multer 1968). At depth, however, the Key Largo Limestone extends northward to at least Miami, and westward to at least the Dry Tortugas (Hoffmeister and Multer 1968). Its thickness has been found to be quite variable, with core borings penetrating sections between 23 and 52 m thick.

The Key Largo Limestone is a typical organic reef composed of *in situ*, wave-resistant components, the most common of which are hermatypic corals. These form the framework of the structure and are responsible for trapping sand-sized carbonate particles in which they are now embedded. Reef framework corals are dominated by the star coral *Montastraea annularis* and several species of brain coral (e.g., *Diploria spp.* and *Porites astreoides*) (Hoffmeister and Multer 1968; Hoffmeister 1974).

Most of the common corals on the present Reef Tract also occur in the ancient Key Largo Limestone. However, the corals found in the Key Largo Limestone are more similar to those of modern patch reefs than to those of the outer Reef Tract (Hoffmeister 1974). A significant difference between corals of the ancient Key Largo and corals of the modern outer Reef Tract is that the elkhorn coral *Acropora palmata*, common in today's outer reef, has never been identified in the Key Largo Limestone (Hoffmeister 1974). This important observation is relevant to the interpretation of how the Key Largo Limestone evolved.

The Miami Limestone consists of two distinct facies, the oolite facies and the bryozoan facies. The oolite facies (also called the Miami Oolite), which is of concern here, overlies the Key Largo Limestone along the Southeast Florida coast and in the southern Keys. The bryozoan facies interfingers with the Key Largo Limestone and is found to the west of the oolite facies. The oolite facies covers the entire Lower Keys, south of Big Pine Key. It increases in thickness to the north, where it reaches a maximum of about 10 m on the northern part of Stock Island, which adjoins Key West (Hoffmeister and Multer 1968). Along the southeastern coastal ridge in the Miami area, the oolite facies reaches a thickness of approximately 12 m (Robinson 1967), and exhibits various degrees and directions of cross-bedding (Hoffmeister 1974).

The Key Largo Limestone originated as a living coral reef that flourished during the sea level high-stand of approximately 125,000 years ago (Perkins 1977). Its total length

of at least 365 km (200 nmi) and its great thickness indicate that it was a major reef system that flourished for at least many hundreds of years (Hoffmeister 1974).

The question of which type of reef ("barrier reef" or "patch reef") formed the Key Largo Limestone has been the subject of much speculation and debate because of difficulties in identifying a precise modern analog. Both patch (platform-interior) reef and barrier (platform-edge) reef types contain a large number of coral species in common, but many of the modern platform-edge reefs are characterized by much more distinct coral zonation and the presence of massive, oriented colonies of *Acropora palmata* extending from the reef crest to a depth of about 4 m (Marszalek et al. 1977; Harrison and Coniglio 1985). In the Key Largo Limestone, the conspicuous absence of *A. palmata*, as well as the preponderance of *Montastraea annularis* and the apparent lack of coral species zonation, have consistently led to interpretation of a patch reef origin (Harrison and Coniglio 1985). Hoffmeister and Multer (1968) proposed that the Key Largo Limestone formed in shallow water as a linear series of coalescing patch reefs that grew behind a protective, but subsequently eroded, shelf-edge barrier reef, which later formed the foundation for the modern shelf-edge reef system. Perkins (1977) also favored a shallow-water, patch reef origin, but in a slightly different context. He suggested that the Key Largo reef initiated at a topographic break in slope near the outer shelf margin and migrated laterally shelfward to its present position in response to rising sea level. A shelf-edge reef, therefore, need not have been present.

Proponents hypothesizing that the Key Largo Limestone originated as shelf-edge reefs cite sediment type, deposit geometry, and spatial relationships as evidence (Harrison and Coniglio 1985). Additionally, they maintain that a seaward barrier would have been too deep for reef growth, and that there is no evidence for marine erosion of a shelf-edge reef system (Harrison and Coniglio 1985). Finally, they attribute the lack of *Acropora palmata* to environmental stress (from cold, nutrient-rich, sediment-laden water spilling off the carbonate platform interior to the northwest) (Harrison and Coniglio 1985).

The Key Largo Limestone and Miami Oolite are believed to have been deposited contemporaneously, as there is no unconformity separating the two units. It is thought that the barrier provided by the growing reefs of the Key Largo Formation increased tidal currents between the Atlantic and Gulf, thereby allowing precipitation and shaping of cross-bedded, oolitic, tidal sand bars (Shinn et al. 1989). As these bars grew by the continued accumulation of ooids, they began to prograde seaward until they eventually buried the northern and southern sections of the reef system (Hoffmeister 1974). West of Key West, the oolite facies submerges and continues westward, forming the bedrock underlying the Holocene Marquesas Keys and the region known as the Quicksands (Shinn et al. 1989). No information exists describing the relationship between the Quicksands and Dry Tortugas to the west. At the Dry Tortugas, however, modern sediments rest on coralline Pleistocene limestones believed to be the Key Largo Formation (Shinn et al. 1989). Strong reversing tidal currents continued to shape the oolite sand bars, forming the northwest-southwest oriented shoals cut by narrow tidal channels that characterize the modern configuration of the Lower Keys (Shinn et al. 1989).

Approximately 100,000 years ago, a major glacial episode initiated a sea level fall. Reefs began to die, and in time became dry land. At its extreme, sea level fell approximately 130 m below its present level. As sea level fell, soils formed, and calcium carbonate leached by rain percolated into the sediment, precipitating a brown, laminated crust, called calcrete. This calcrete crust is used to distinguish between today's reefs and those of the past. Approximately 18,000 years ago, sea level began to rise again as a result of melting glaciers. It was not until about 6,500 years ago that sea level was high

enough to initiate new reef growth in the Keys (Shinn 1988). Many present-day corals rest directly on the old calcrete crust (Shinn 1988). Therefore, the ancient reefs and sand shoals that formed 125,000 years ago laid the foundation for today's reef distribution.

The interplay between topography and sea level rise explains why modern reef development is poor off the Middle Keys as compared to the flourishing reefs off the Upper Keys, and to a lesser extent, the Lower Keys (Shinn 1988). As sea level began flooding the continental shelf, between 6,000 and 10,000 years ago, seawater spilled over the edge and began flooding low areas behind the reefs and Keys (**Figure 2.4**) (Shinn 1988). At times, unusually cold storms would come in from the north, sweeping a lethal combination of cold, nutrient-rich, sediment-laden water through large tidal passes in the Middle Keys and onto the reefs (Marszalek et al. 1977; Shinn 1988). Reefs that previously flourished opposite these major tidal passes began to diminish. Only off large islands, such as Key Largo, did elkhorn coral reefs continue to thrive. The barrier provided by Key Largo, and the less complete barrier formed by the Lower Keys, prevented or retarded deleterious waters of Florida Bay and the Gulf of Mexico from invading the reefs (Shinn 1988).

Modern Configuration

The modern configuration of the submerged South Florida continental shelf, seaward of the Keys, is depositional in nature. Enos (1977) subdivided the shallow shelf into the inner shelf, inner shelf margin, outer shelf margin, and shallow slope. The inner shelf consists of Florida Bay and its westward transition to the Gulf of Mexico, and will be discussed in a subsequent section.

The inner shelf margin, known as Hawk Channel (**Figure 2.4**), typically slopes gradually (0.06°) seaward from the rocky shoreline of the Keys to a depth of about 5 m, where it deepens into a depression about 8 to 15 m deep and up to 2.5 km (1.4 nmi) wide. Patch reefs, tidal deltas, and small sediment banks are its prominent features.

Sediments of the inner shelf margin consist of 10 to 50% fine-grained (<63 μm) material rich in *Halimeda* (green alga) and mollusc fragments (Enos 1977). In general, percentages of molluscs and foraminifera decrease seaward, and percentages of coral fragments increase. The dominant mineral is aragonite, reflecting the relative abundance of *Halimeda* (Enos 1977).

The largest sediment accumulations on the inner shelf margin are prisms that wedge out against the sloping Pleistocene rock near the Keys. Sediments are interpreted to have been produced *in situ* by calcium carbonate production (Enos 1977). Deposition occurred in an environment at least as restricted as the inner shelf margin at present (Enos 1977). Restricted circulation on the wide, shallow shelf margin results from reefs and sand shoals near the shelf edge that form a partial barrier to open sea processes. Wedges are found seaward of Pleistocene topographic highs (where they are continuous) and extend to near or above sea level, but they are not found at all of these locations (Enos 1977).

Patch reef banks on the inner shelf margin are probably dependent upon local skeletal production (Enos 1977). Banks may have originally formed by mechanical concentration of fine-grained material, followed by in-place production of patch reefs. Many of the patch reef banks are controlled by antecedent topography (presumably, a bank whose original location and development was influenced by rock-floor features) (Enos 1977). Several patch reefs on the inner shelf are formed directly on Pleistocene

rock, without an associated sediment bank. Virtually no loose sediment surrounds these coral heads, which rise up to 5 m from the bottom. One distinct possibility is that these reefs may be so young and vigorous that little or no loose sediment has been produced (Enos 1977). Presumably, the ecological factors controlling patch reef development on the inner shelf margin are similar to those for the outer (shelf-edge) reef community, except that less energy is required. These lower energy levels require smaller or less stable hard substrates for initial coral attachment (Enos 1977).

Tides, focused into strong currents by constriction between the rocky Florida Keys, have built large banks of sediment (tidal deltas) on the inner shelf margins. Transported, fine-grained, carbonate-rich sediment, available from the inner shelf (Florida Bay) and areas immediately adjacent to the deposits, is probably the major component of the tidal deltas. Tidal deltas are focused primarily by the ebb flow of tides through the relatively narrow passes between the Keys. Hence, no tidal deltas have developed seaward of the wide tidal passes of the Middle Keys. In addition to current strength, the balance between sediment supply and wave energy is important for determining the size and form of tidal deltas (Enos 1977). Tidal deltas on the inner shelf margin, however, can only develop where large, oceanic waves are dampened by shoals at the shelf margin. Tidal deltas are the only major sediment accumulations on the inner shelf margin that are perpendicular to the shelf edge (Enos 1977).

Aside from tidal delta and patch reef banks, the only banks on the inner shelf margin are the comparatively small, isolated, skeletal grainstone shoals and muddy shoals (Enos 1977). The origin of these banks is interpreted to be controlled initially by a slight break in slope. Once a shoal fringe community (commonly dominated by *Porites* and *Goniolithon*) is established, it becomes a great sediment contributor. A bank may eventually develop from differential carbonate production by the shoal-fringe community and by other carbonate-producing communities growing behind the protective fringe. This may be the origin of many patch reef banks that developed from muddy banks, and it would explain why many patch reefs are located on slight breaks in slope of the underlying Pleistocene rock surface (Enos 1977).

The outer shelf margin averages about 3 km (approximately 1.5 nmi) in width. It is sharply delineated from the inner shelf margin in many places by the inner edge of skeletal sand shoals, known as White Bank, or by patch reef banks (Enos 1977). Banks are in water as shallow as 1 to 3 m. A rippled sand bottom slopes seaward from the banks to a depth of 9 to 12 m near the shelf edge. In areas of active reef growth at the shelf edge, the reef and surrounding sediment bank may extend upwards, nearly to sea level. Where there is little or no active reef growth, a rocky shoal is generally produced by dead reefs that flourished during early flooding of the Holocene sea level transgression. Piles of relatively coarse reef rubble have been built up to sea level behind several of the living outer reefs and shallowest dead reefs. From the shallow shelf break, the seafloor slopes seaward at a gradient as high as 10°. At depths of 25 to 30 m, the bottom begins to slope more gently toward the deeper slope break at the edge of the continental shelf (Enos 1977).

The major feature of the outer shelf margin is the Reef Tract, an arcuate belt 5 to 10 km (2.7 to 5.4 nmi) wide with relatively open circulation. Outer reefs are buttresses of living and dead reefs at the shelf break and the much larger banks of unbound reef-related sediments immediately adjacent to buttresses (Enos 1977). Locations of outer reefs appear to be controlled by the Pleistocene shelf break, although some reef buttresses are as much as 1 km (0.5 nmi) behind it. The shelf break serves to focus wave energy and water circulation, which aids in the continued development of reefs.

A major characteristic of reef flanks is the alternation of spurs (finger-like projections) and grooves (channels) (Shinn et al. 1989). Spurs and grooves are almost always oriented into the sea, normal to the reef front. They occur on reefs of the outer Reef Tract but are poorly developed or absent on patch reefs. Their spacing is believed to be controlled by wave energy; where waves are large, formations are better developed and spaced more narrowly (Shinn et al. 1989). Spurs may be the result of erosion or construction. Core drilling at Looe Key Reef, offshore Big Pine Key in the Lower Keys, penetrated a spur-and-groove system lying over carbonate-reef sand (Shinn et al. 1981). Only the thin seaward end of the spurs appeared to be rooted in underlying bedrock. Based upon these data and other observations, Shinn et al. (1981) suggested that most shallow spurs and grooves in active coral reefs of the Keys are constructional in origin and not necessarily initiated or controlled by bedrock topography. They further suggested, however, that spurs and grooves in deeper (>15 m), fore-reef areas off the Keys may be erosional in origin. Whether spurs and grooves are constructional or erosional, they act as breakwaters that appear to dampen the energy of incoming waves. Although their origin and spacing are still not completely understood, they perpetuate because storm seas tend to periodically dislodge corals that become attached in grooves where carbonate sand may accumulate (Shinn et al. 1989).

Sediments along the outer Reef Tract have long been thought to consist mainly of the alga *Halimeda*. Recent work, however, has shown that sand-sized sediments in the Lower Keys adjacent to Looe Key Reef are composed mainly of coral, with subordinate amounts of mollusc and *Halimeda* fragments (Lidz et al. 1985). There seems to be a trend of decreasing *Halimeda* sand content from north to southwest along the Reef Tract, and then an increase of *Halimeda* farther to the west (Shinn et al. 1989). Lidz et al. (1985) concluded that *Halimeda* particles are concentrated in areas where reefs are healthy, whereas coralline particles are concentrated where reefs are in a state of decline. Dead corals are more readily attacked by boring organisms (e.g., sponges, molluscs, algae, pholid clams, and parrotfish), thus producing particulate coral, whereas live coral is less subject to bioerosion. Thus, the health of the reef may, to some extent, control the composition, and possibly the grain size, of surrounding sediments.

Another prominent feature of the outer shelf margin is shelf-margin sand shoals. The largest is White Bank, a continuous shoal approximately 40 km (22 nmi) long and 1 to 2 km (0.5 to 1 nmi) wide, located just inside the Reef Tract in the Upper Keys. Whether White Bank formed from a slight rock-floor high, from coalescing patch reefs, or from hydraulic factors, is still not known. Enos (1977) suggested that the shoals consist primarily of material derived from outer reefs that is concentrated by hydraulic processes. Rock-floor relief and patch reef locations are considered secondary factors. Sediments consist of loose, often fairly well-sorted, clean, rippled, *Halimeda*-rich sand (Multer 1977). Enos (1977) maintained that sediments are derived primarily from the outer reefs because (1) White Bank is located immediately adjacent to maximum outer reef production; (2) *in situ* sediment production is very low; (3) skeletal sand transport is mainly landward; and (4) some sediment parameters show gradational trends from the reefs landward across the outer shelf margin. White Bank tends to be wider and thicker where the Reef Tract is best developed, such as off Key Largo (Enos 1977). The low standing crop of organisms on White Bank indicates that skeletal production is negligible. White Bank is asymmetric in cross section, with a steeper landward side, suggesting landward migration and a seaward (Reef Tract) origin of sediments. The relative abundance of coral and red algae grains, the best reef indicators, decreases steadily in a landward direction from the outer reefs. White Bank is probably not longer than 40 km (22 nmi) because sand supply in areas of less reef productivity is inadequate to build a large shoal. Consequently, sand shoals inside of the poorly developed shelf-edge reefs of the Middle Keys are either non-existent or underdeveloped.

Patch reef banks are also important features on the outer shelf margins. Patch reef banks are prominent as a northward continuation of the trend of large, White Bank sand shoals (Enos 1977). Patch reef banks are similar in origin and configuration to those described previously for the inner shelf margin.

Scant information is available for the outer Reef Tract to the shelf break at approximately 100- to 200-m water depths. Multer (1977) points out that little rubble is found seaward of the Reef Tract--an observation that contrasts with the idea that rubble is generally found in front of outer reefs. The small amount of rubble may be due to (1) the lack of material transported seaward by ebb tides; (2) the lack of material slumped from the platform edge; and (3) the lack of subaerially-eroded material available from the previous emergence (Multer 1977).

Sediment accumulation patterns on the Southeast Florida continental margin seaward of the Keys are controlled principally by skeletal productivity, mechanical redistribution, pre-existing (antecedent) topography, and the continuously evolving depositional topography (Enos 1977). The most important and direct control seems to be the organic production of carbonate sediments. This is not surprising, because virtually all of the sediment being contributed today is of skeletal origin. As mentioned previously, variations in organic productivity correlate with the large-scale lateral variations in sediment accumulation along the shelf margin. The coral reef environment is the major producer of carbonate sediment, and therefore, in effect, is a dominant regulator of sediment distribution patterns on the shelf.

Mechanical redistribution of sediment is a second important control of sediment distribution patterns. In many cases, mechanical redistribution (sediment transport) is secondary only to organic productivity. Organic productivity controls the location of deposits, but transport processes regulate the geometry and depositional structure (Enos 1977). *In situ* skeletal production is appreciable on the shelf, but probably subordinate to mechanically redistributed deposits (Enos 1977). Large, high-energy waves and storm tides are the most effective sediment transporters (Shinn et al. 1989).

Antecedent, or pre-existing, topography is sometimes a major control over location and geometry of sedimentary deposits on the outer shelf margin. Antecedent topography influences the development of some outer shelf reefs as well as some outer shelf margin sand shoals, including possibly White Bank (Enos 1977). In general, the direct influence of antecedent topography on sediment distribution is lessened as underlying surfaces become covered by Holocene sediments (Enos 1977).

As Holocene sediments are deposited, the role of contemporary topography in controlling sediment distribution becomes greater. At present, 75 to 95% of the Pleistocene rock surface is covered with Holocene deposits, and direct influence is exerted by the evolving seafloor topography. The differential carbonate productivity that can arise from very slight relief accentuates depositional relief (Enos 1977). It is estimated that as more modern sediments are deposited, the influence of contemporary depositional topography on sediment distribution patterns will become much greater and that of antecedent topography correspondingly less.

FLORIDA BAY

Florida Bay is a shallow, triangular embayment with an area of about 1,550 km^2. It is bordered on the north by the Everglades, on the southeast by the Florida Keys, and rather arbitrarily on the southwest by the Gulf of Mexico (**Figures 2.1** and **2.4**). Although Florida Bay is open to the southwest, open-water effects from the Gulf of Mexico are dampened by anastomosing mudbanks, which cordon the Bay into a series of

basins (i.e., lakes) (Scholl 1977; Merriam 1988). Average water depths are approximately 1.5 to 2.0 m, but reach up to about 3.0 m in the deepest parts in the southwest. Ginsburg (1956) divided Florida Bay into two subenvironments: the interior and the margin. The interior is characterized by low tidal range, weak currents, and large seasonal variations in salinity and temperature. The surrounding marginal environment is one of more uniform water characteristics and stronger water motion because of good tidal exchange with the Gulf of Mexico and Atlantic Ocean.

Florida Bay has been studied extensively during the past three decades, probably because it is a classic example of a modern, dynamic, lime-mud factory that is easily accessible to geologists. Examples of important contributions can be found in Ginsburg (1956), Gorsline (1963), Price (1967), Ginsburg (1972), Enos and Perkins (1977), Multer (1977), and Merriam (1988). Merriam (1988) described three distinct segments of Florida Bay investigations: (1) early exploration and description (1850 to 1953); (2) general stratigraphy and sedimentology (1953 to 1977); and (3) detailed, in-depth studies (1977 to present). Since 1977, studies have concentrated on generation, distribution, accumulation, alteration, and preservation of lime mud on the drowned Miami Limestone surface during approximately the past 5,000 years. Many of these detailed studies have focused on only a small segment of Florida Bay, as opposed to bay-wide investigations characteristic of previous years.

Geologic Development

Florida Bay is underlain by the Miami Limestone, which slopes slightly to the southwest (Hoffmeister 1974; Merriam 1988). As discussed previously, two facies of the Miami Limestone are recognized: the bryozoan facies and oolite facies. Until recently, it was thought that the oolite facies underlies the entire Bay. Merriam (1988), however, cited evidence (from recent bedrock drilling in the Bay) that at least part of the Bay is underlain by the bryozoan facies. Both facies are stratigraphically equivalent to the Key Largo Limestone (Enos and Perkins 1977). The oolite facies has been described previously (see Florida Keys and Reef Tract section). The bryozoan facies is so named because as much as 70% of the rock may be composed of colonies of the bryozoan *Schizoporella floridana*. After bryozoans, pellets are the most abundant constituent, with lesser amounts of miliolids, peneroplids, and ooids. Locally, the unit contains burrows and calcareous worm tubes (Merriam 1988).

Recent geologic development began approximately 100,000 to 125,000 years ago when coral reefs, which later formed the basis for the Florida Keys, were flourishing. The sea at that time stood approximately 6 m higher than at present, and the area today known as Florida Bay was a lagoon between the living coral reef and the mainland to the north. Within this lagoon, deposits of oolitic limestone, which would eventually cover the Bay floor and bury parts of the Key Largo Limestone reefs, were being formed (Hoffmeister 1974). As sea level lowered in response to the ensuing Wisconsin glaciation (which existed from about 75,000 to 10,000 years ago), Florida Bay became dry land, as did the Keys and Reef Tract. During exposure, the Florida Bay land surface was heavily eroded, and the unconsolidated carbonate sediments became hardened to form the Miami Limestone. With the Holocene rise in sea level, the karst surface of the Miami Limestone was slowly inundated from the southwest.

Flooding of Florida Bay probably began 4,000 to 5,000 years ago (Scholl 1977; Merriam 1988; Quinn and Merriam 1988). During very early flooding, the Bay resembled the modern Everglades. It was low-lying, covered with Everglades vegetation, dotted with freshwater lakes, and streaked with rills and sloughs. Marine waters began to spread over the Bay through channels between the Keys. The environmental change from freshwater to seawater introduced marine animals and plants into the region.

Dominant forms included mangroves, calcareous algae, and marine molluscs (Hoffmeister 1974). Mangroves played an important role in early development of the Bay. As seawater reached the low-lying rill valleys and gradually extended northward along their channels, colonization by mangroves and seagrasses began. Together, these plants formed baffles that trapped fine-grained sediments, principally lime muds from *Penicillus* spp. and other green algae, and peat fragments from the disintegration of mangroves (Hoffmeister 1974). As mangrove colonization continued northward during rising sea level, the southern parts of the Bay deepened. Other banks formed perpendicular to the original north-south oriented rill banks, creating an irregular network of banks and basins (lakes). Tidal currents and storm waves created larger lakes, especially in the south, by the destruction of some of the separating walls. The original configuration of banks and basins can still be seen along the northern parts of the Bay, where tidal current and storm wave activity have been too weak to destroy separating banks. Here basins are smaller and more numerous.

Modern Configuration

The modern configuration of Florida Bay has been termed a basin-in-basin honeycomb (Price 1967). In general, the modern Bay consists of numerous rimmed, flat-bottomed basins, mostly oval, which are enclosed by marly, peaty rims in <1 m water depth. Scholl (1966) identified 17 of these "intra-bay lakes" (basins), which are interconnected by randomly located openings. Submerged ridges, which appear to be remnants of once more-continuous basin rims, extend into many of the basins. Submerged ridges are of irregular length, and their summits decline basinward at various slopes (Price 1967). Studies on individual basins have shown them to be saucer-shaped in cross section, with thin sediment cover in the center (Sorensen 1985; Merriam et al. 1987).

Basins are defined by mudbanks or low, mangrove-fringed islands. Mudbanks are typically asymmetrical, with the north and west sides steeper and more shelly (Merriam et al. 1987). Storms from the north and west winnow the fine-grained sediments, leaving a lag of coarser-grained material on the north and west side of the banks. Banks are composed of light-gray, fine-grained micrite intercalated with layers of coarse shell hash, which are probably storm layers (Merriam et al. 1987). Both positions and compositions of banks are continuously being modified, primarily by physical processes (Kick 1981). Mudbanks probably maintain their relief by higher organic production on the shallow bank tops (Sorensen 1985).

Islands in Florida Bay are typically oval-shaped in map section and saucer-shaped in cross section. Surficially, many islands consist of an exterior fringe of red mangroves, an interior fringe of black mangroves, and an open central tidal flat or pond (Merriam et al. 1987; Quinn and Merriam 1988). The principal depositional environments of islands, in upward succession, are as follows: (1) freshwater pond; (2) coastal mangrove swamp; (3) marine basin (lake); (4) mudbank; and (5) island (Enos and Perkins 1979). The generally accepted model for the evolution of Florida Bay islands, based upon this depositional sequence, is that most islands developed from underlying mudbanks, probably by mangrove colonization (Enos and Perkins 1979). Recent evidence documents that at least some islands nucleated from a supratidal precursor consisting of eroded remnants of coastal tidal flats or local topographic highs that remained supratidal throughout the Holocene sea level rise (Quinn and Merriam 1988).

Because of the recognition of Florida Bay as a modern lime-mud factory, surface sediments and sedimentary processes have been studied in detail. Unconsolidated sediments in Florida Bay typically consist of >90% calcium carbonate. The remainder consists primarily of quartz, the remains of siliceous organisms (radiolarians and sponge

spicules), and organic matter with minor amounts of clay minerals (Scholl 1977). Grain size of the carbonate fraction ranges from large mollusc or coral fragments, measuring several centimeters or more in length, to ultra-fine particles <1 μm in length (Scholl 1977), commonly resulting in a bimodal size distribution (Kick 1981; Tyson 1981; Merriam 1989). Mudbanks consist predominantly of silt-sized carbonate particles (Scholl 1977), as do basin sediments (Tyson 1981). Most carbonate sediments are skeletal in origin (Ginsburg 1956), derived from calcified parts of plants and animals. The greatest contributors are molluscs, foraminifera, and algae. Fragmentation of coarse skeletal debris to particles as small as 20 μm may be accomplished by physical abrasion and bioerosion (Scholl 1977), although Kick (1981) reported that biological crushing (by crabs, fish, and octopuses) constitutes over 90% of broken grains in Peterson Key Bank sediments. Some sediment-ingesting organisms also increase the grain size of calcareous muds by aggregating fine-grained matter into fecal pellets (Ginsburg 1972). Scholl (1977) suggested that fecal pellets may constitute as much as 50% of the sediments. Based on regression analysis, Sorensen (1985) reported that the dominant grain size class may be a function of water chemistry (e.g., salinity, dissolved carbon dioxide, and dissolved oxygen).

The carbonate fraction of silty muds in Florida Bay surface sediments consists of four main minerals: aragonite, high-magnesium calcite, low-magnesium calcite, and dolomite (listed in order of abundance). Seventy percent or more of the sediments consist of aragonite or high-magnesium calcite, the metastable carbonate minerals (Gorsline 1963; Ginsburg 1972). Aragonite is the dominant mineral in Florida Bay surface sediments, averaging 60 to 65%, but reaching up to 100% (Ginsburg 1972). Most aragonite occurs as aggregates of light-brown crystals, but a small amount consists of acicular needles which are generally <10 μm in length (Scholl 1977). The origin of aragonite is somewhat controversial. Muller and Muller (1977), Scholl (1977), Kick (1981) and Tyson (1981) all report that aragonite in specific portions of Florida Bay is derived primarily from molluscs. Bathurst (1975) further maintains that the volumetric importance of molluscan material in Florida Bay sediments far outweighs the algal contribution. Conversely, Stockman et al. (1967) suggest that green algae *Penicillus* spp. are major contributors in fine aragonitic muds, and the principal source of aragonite needles. In addition, they suggest that the present lime-mud production rate by *Penicillus* (0.3 cm/1,000 years) could account for one-third of the mud present in northeastern Florida Bay today. More recently, Sorensen (1985) concluded that algae are more important contributors than molluscs in selected Florida Bay basin sediments. Strontium content in aragonite muds is variable, with high concentrations (averaging 8,000 to 9,000 ppm) in bank and island muds, and lower concentrations (averaging 3,000 to 5,000 ppm) in basin floor muds (Gorsline 1963). This variance suggests different sources for bank/island vs. basin muds.

High-magnesium calcite (>4 mole percent $MgCO_3$) constitutes approximately 20 to 30% of sediments in Florida Bay (Ginsburg 1972; Scholl 1977). High-magnesium calcite is derived principally from benthic foraminifera, especially the forams *Peneroplis proteus* and *Archais angulatus* (Scholl 1977). Various other marine plants and animals supply secondary amounts of high-magnesium calcite to the sediments of the Bay. Analysis of pore fluids at specific locations indicates that the metastable, high-magnesium calcite fraction of sediments is converting to the more stable, low-magnesium calcite form (Merriam 1988).

Low-magnesium calcite (<4 mole percent $MgCO_3$; essentially common calcite) is the stable form of calcium carbonate and constitutes only about 15% of Florida Bay sediments (Ginsburg 1972; Scholl 1977). The bulk of low-magnesium calcite is believed to be principally derived from molluscs; however, some must be added by the conversion from metastable forms.

Dolomite accounts for a maximum of about 5% of most Florida Bay sediments (Scholl 1977). Protodolomite possibly forms in some basin environments (Merriam 1988), and has been reported as recently formed on Sugarloaf Key, in the Lower Keys (Shinn 1972). Radiocarbon dates, however, show that some dolomite rhombs are much older than surrounding Bay sediments and that they were most likely transported from local, older limestones and dolomitized zones of Tertiary age (Gorsline 1963).

Organic content in Florida Bay sediments is typically high, in part because of the high productivity. Other factors affecting organic content are reduced circulation and a general low permeability of fine-grained sediments, which result in rapid development of strong reducing conditions a few centimeters below the sediment-water interface (Gorsline 1963). The average organic carbon content is approximately 3% by weight (Ginsburg 1972), but the percentage may be much higher in peaty layers, which are common in island environments.

Clay minerals constitute a very small proportion of Florida Bay sediments (Gorsline 1963). Chlorite and smectite dominate the clay size fraction of Recent sediments, followed by lesser quantities of illite and kaolinite (Manker and Griffin 1977). Chlorite is derived from the Atlantic coast and eastern Everglades, and is introduced by streams and by tidal channels through the northern Keys (Manker and Griffin 1977).

The major influence on modern sediment distribution patterns appears to be wind-driven currents, especially those generated by periodic storms. Merriam et al. (1987) identified layers of relatively coarse-grained material, which they interpret as "storm layers," intercalated within otherwise soft, finer-grained sediments on Florida Bay mudbanks. Tyson (1981) suggested that easterly, wind-driven waves and currents transport fine-grained sediments to the fringes of basins, and also create an environment along the eastern perimeter of basins where more fine-grained material accumulates. He further suggested that this lee environment provides suitable substrate for infaunal bivalve communities. As bivalves die, they contribute to the coarse-grained fraction of the sediment, resulting in the bimodal size distribution. Tides may be the dominant physical process influencing sediment distribution patterns in some areas, especially those sheltered from wind-driven effects (Roberts et al. 1977). The ultimate effects of tides on sedimentary characteristics and depositional environments are a function of parameters including strength and frequency, as well as the individual physical configuration of each depositional basin. Merriam et al. (1985) suggested that water chemistry, along with physical factors, mainly determine distribution and accumulation of Recent Florida Bay sediments.

Recent evidence suggests that sediments are periodically being exported out of Florida Bay. Large, ebb-tidal deltas seaward of restricted passes separating the Keys are believed to have been constructed of fine-grained, calcium carbonate-rich sediments transported from Florida Bay (Enos 1977). The poor development of coral reefs off the Middle Keys has also been attributed, in part, to the export of fine-grained Florida Bay sediments. Sediments are transported through the wide passes and onto the Reef Tract, where they inhibit coral development (Marszalek et al. 1977; Shinn 1988). Roberts et al. (1982) presented satellite data documenting the export of cold, dense water out of Florida Bay during winter storms. Sediment accumulations on the upper Southwest Florida slope are interpreted to have developed, in part, by transport of these sediments from Florida Bay, by tidal and storm-generated currents (Brooks and Holmes 1989). In addition, Stockman et al. (1967) have shown that the production of biogenic lime mud is in excess of the total accumulation in Florida Bay. The surplus, therefore, must be exported from the Bay.

In conclusion, a substantial amount of sedimentological data currently exists on Florida Bay. It is now becoming possible to simulate processes operational in the bay and to more accurately predict ultimate effects of these processes. In a simulation utilizing basin configuration, sea level fluctuations, and sediment generation rates, Merriam (1988) showed that Florida Bay is presently infilling from the west and the north, and that sea level is the dominant factor in shaping the end result.

SOUTHWEST FLORIDA CONTINENTAL MARGIN

The Southwest Florida continental margin includes the southern portion of the West Florida continental shelf, and the slope bordering the southern Straits of Florida (**Figure 2.1**). It is bordered by Florida Bay, the westward extension of the Florida Keys and Reef Tract, and the Southwest Florida coast north of Cape Sable. The Southwest Florida margin contains a variety of environments, from the more restricted zones adjacent to Florida Bay and along the Southwest Florida coastline to the more open marine conditions of the Southwest Florida shelf and slope.

Although the Southwest Florida margin is much larger than the Florida Keys/Reef Tract and Florida Bay, the area has been little studied. Investigations on the open portion of the margin have only recently been documented, concentrating on the outer shelf (Holmes 1981; Martin 1984; Holmes 1985) and the upper slope bordering the southern Straits of Florida (Brooks 1986a; Brooks and Holmes 1989). Studies on the inner shelf, coastal zones, and more protected parts of the shelf bordering Florida Bay have concentrated on specific areas or environments such as Cape Sable (Gebelein 1977; Roberts et al. 1977) and the Cape Romano/Ten Thousand Islands area (Holmes and Evans 1963; Tanner et al. 1963; Parkinson 1987; Davis and Klay 1989). In addition, considerable attention has been focused on the shelf-edge carbonate banks, specifically the Marquesas Keys and Dry Tortugas (O'Neill 1976; Shinn et al. 1977; Halley 1979; Hudson 1985; Shinn et al. 1989), both of which have been discussed briefly in the Florida Keys/Reef Tract section.

Geologic Development

Although it is not possible to construct a detailed history of the Southwest Florida shelf, its development seems to have been strongly controlled by recent sea level fluctuations. The foundation for the modern configuration is a karst surface that possibly developed in Miocene strata (Holmes 1981). Karst development may have been the result of a Late Miocene sea level fall that exposed part of the shelf, thereby producing conditions favorable for significant groundwater head, eventually resulting in large and numerous solution features (Holmes 1981; Doyle et al. 1985). Subsequent high-frequency sea level fluctuations in the Pliocene and Pleistocene produced a sediment wedge that underlies the outer shelf and upper slope. The age of the material is not accurately known, and its historical (depositional) record, as well as detailed characteristics, have been repeatedly disturbed by subsequent sea level fluctuations. Only deposits of the most recent transgression remain relatively undisturbed. During early flooding of one of the mid-Pleistocene transgressions, a double reef system formed on the outer shelf (Holmes 1981). Based on seismic interpretation, it appears that the outer (lower) reef formed first (Holmes 1985). It is unclear whether the inner (upper) reef formed later during the same transgression, or during a minor sea level regression (Holmes 1981). During this time period, the shelf started to prograde southward, overlapping the Miocene shelf break to the south (Holmes 1981; Brooks and Holmes 1989).

During initial flooding of the Holocene transgression, approximately 10,000 years ago, a central-shelf reef complex (Pulley Ridge) began to develop (Holmes 1981).

Development appears to have been vigorous, as the reef buries both the Miocene shelf break and the shelf-edge double reef system described above (Holmes 1981). The formation of this reef complex during a sea level still-stand was the major process responsible for carbonate deposition on the inner portion of the Southwest Florida shelf (Holmes 1981).

The shelf-edge carbonate banks were the last to form. Banks, including the Marquesas Keys, Dry Tortugas, and possibly submerged banks to the west, are believed to be Holocene in age, but founded on Pleistocene topographic highs (Shinn et al. 1977). Banks have encroached over previous reefs and slope deposits bordering the southern Straits; they are currently active and are believed to be building to the west (Holmes 1981).

The Southwest Florida upper slope has been the site of extensive deposition throughout at least the Late Quaternary and Holocene (Brooks 1986b). Based on seismic data and sediment cores, the primary control over recent development of the slope is attributed to high-frequency sea level fluctuations (Brooks 1985). Nine depositional sequences have been identified, each bounded by an erosional unconformity (Brooks 1985). During that portion of the sea level cycle when the shelf surface was flooded, carbonate sediments were produced on the shallow shelf surface, swept southward off the platform, and deposited rapidly on the upper slope (Brooks and Holmes 1989). During sea level low-stands, the shelf surface was exposed, and no off-shelf transport took place. Instead, erosion of the previously deposited sequence occurred due to an increase in the erosive capacity of the Florida Current during glacially-induced sea level low-stands (Brooks and Holmes 1989). Off-shelf transport during sea level high-stands was augmented by the absence of a shelf-edge reef system, which enabled the continued seaward progradation of the upper slope (Brooks and Holmes 1989).

The nearshore portion of the Southwest Florida margin is underlain by the Pliocene Tamiami Formation and the Pleistocene Miami Limestone. The northern part, near Cape Romano, is underlain by the Tamiami Formation; the southern part, toward Cape Sable, is underlain by the Miami Limestone (Enos and Perkins 1977). Overlying these carbonate units is an accumulation of principally Quaternary terrigenous clastics (Davis and Klay 1989). The sequence thins rapidly toward the south and offshore. It is thickest near the tip of Cape Romano and the Ten Thousand Islands region (Davis and Klay 1989).

During the midst of the Holocene sea level transgression, approximately 7,000 years ago, low-energy, open-marine conditions existed in the area. Sediments accumulated largely as a result of reworking of older sediments. As sea level rise slowed (about 3,500 years ago), the development of the barrier island system north of Cape Romano began contributing quartz sands to the system (Davis and Klay 1989). Sands were sorted and molded into linear ridges by tidal currents, longshore drift, and wave activity, which created a system of shoals south of Cape Romano (Holmes and Evans 1963; Tanner et al. 1963; Davis and Klay 1989). In the Cape Sable region, Pleistocene terrigenous clastics were being eroded by transgressing seas. The absence of a supply has kept the region relatively sediment-free throughout the Holocene (Davis and Klay 1989). Parkinson (1987) identified a lower and upper sequence of Holocene sediments in the Ten Thousand Islands, which he attributed to changing rates of sea level rise. The lower unit is a transgressive unit and reflects a relatively rapid rise of approximately 26 cm/100 years. The upper sequence is biogenically shoaling upwards, and is interpreted to represent a decrease in sea level rise (to <10 cm/100 years) at approximately 3,500 years ago.

Modern Configuration

The modern Southwest Florida continental margin (**Figure 2.1**) is part of the only wholly carbonate margin in the U.S. It exhibits a relatively smooth surface that slopes very gently seaward. The shelf-slope transition is gradual, with no shelf-edge reef rim or precipitous escarpment that is characteristic of many carbonate platforms.

Holmes (1981, 1985) recognized eight morphologic units on the Southwest Florida margin. Four of the eight are within the study area, including the inner shelf, outer shelf, upper slope, and southern (outer shelf) banks. **Figure 2.5** shows the modern surface facies of the Southwest Florida margin (Holmes 1985).

The inner shelf extends from the coast to a water depth of 70 m, some 210 km (113 nmi) from the coastline. It dips gently seaward at approximately 0.02°. The surface of the seafloor of the innermost portion, from the coast to a depth of 40 m, is pockmarked by circular depressions, some as large as 2 km (1 nmi) in diameter (Holmes 1985). Depressions are interpreted to represent a karst surface (Holmes 1981). In water depths of 40 to 70 m, the seafloor is relatively smooth and featureless. The karst surface that prevailed landward is present, but buried by carbonate sediments, presumably derived from a mid-shelf reef system. The sediment body is wedge-shaped, thickening seaward (Holmes 1981).

Surface sediments of this part of the margin have not been studied in detail. High-resolution seismic reflection profiling reveals a thin veneer of modern sediments overlying the karst surface (Holmes 1981; Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1983). This sand veneer, consisting of a mix of carbonate and quartz, appears to be mobile; sand movement periodically exposes the underlying limestone surface and allows colonization by sessile epifauna such as sponges and corals (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1983) (see **Chapter 5**). Sediments are predominantly sand-sized, but tend to become finer to the south, where silt-sized sediments dominate (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1983). In the southernmost portion, silt-sized sediments reach approximately 10 m in thickness at the 40-m bathymetric contour; no limestone outcroppings have been identified, and no hard bottom biological communities have been noted (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1983, 1985).

Two distinct sediment types have been identified on the inner shelf (Martin 1984). From the coast to a depth of about 15 m, approximately 32 km (17 nmi) seaward, is a zone dominated by terrigenous clastic material, predominantly quartz. Seaward of this quartz band, sediments consist principally of calcium carbonate. Sediments in the nearshore quartz band consist chiefly of mature, fine quartz sand believed to be derived from adjacent rivers and beaches, and from ancient coastal plain sediments inundated by rising sea level (Martin 1984). Calcium carbonate-rich sediments, seaward of the quartz band, have been described as a shell hash composed chiefly of mollusc shell fragments, along with subordinate amounts of foraminifera and calcareous algae (Martin 1984). A diffuse zone of mixing separates the carbonate and quartz end members (Martin 1984).

The inner shelf is separated from the outer shelf by Pulley Ridge, a 10 km (approximately 5 nmi) wide feature interpreted by Holmes (1981) to be a biohermal complex, and revealed by underwater television to be capped by coralline algal growth currently supporting a dense sessile epibiota (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1983, 1985). The complex forms a series of steps dropping from 70- to 90-m depths, and divides the 0.02° seaward-dipping inner shelf from the 0.07° more

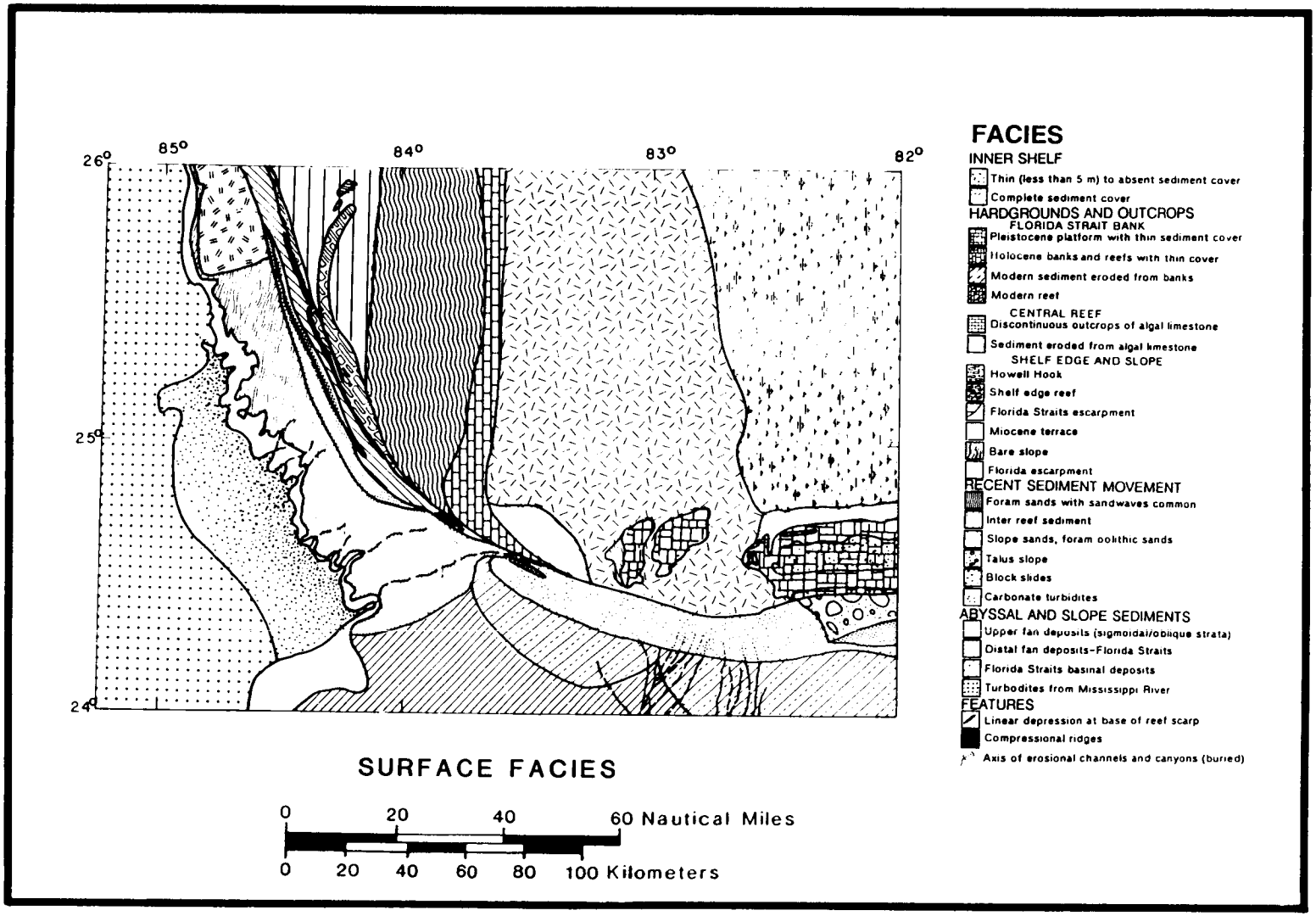

Figure 2.5. Surface facies of the Southwest Florida continental margin (From: Holmes 1985).

steeply-dipping outer shelf (Holmes 1985). Pulley Ridge is partially exposed or covered by a thin veneer of carbonate-rich, sand-sized sediments (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1985).

The outer shelf extends from approximately 90-m water depths at Pulley Ridge to the shelf-slope transition at 100- to 200-m water depths. The surface is comparatively smooth, with a gentle seaward dip of approximately 0.1° (Holmes 1981). Locally, the smooth surface is broken by wave-cut terraces, 2 to 3 m in height, believed to have formed during hiatuses in sea level rise (Holmes 1981). Shallow pockmarks (sea-floor depressions) have been identified in water depths of 100 to 150 m (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1985). These features, which are nearly circular, have a central depression approximately 20 to 30 m in diameter and are <2 m deep (Holmes 1981). Like pockmarks on the inner shelf, those on the outer shelf are probably related to the paleohydrology of South Florida (Holmes 1981).

Sand waves are present across the entire width of the outer shelf zone. They occur in sets of four to five, with wave heights of approximately 5 m and wave lengths ranging from 250 to 2,000 m (Holmes 1985). Sand waves are strongly asymmetrical and southward facing, indicating a strong southerly flow and transport of sediments (Neurauter 1979; Holmes 1981). Sediments in sand waves are wholly biogenic, dominated by planktonic foraminifera.

The shelf edge is marked by an inactive double reef complex. The shallowest reef, cresting from 130- to 150-m water depths, does not closely parallel the shelf edge, but veers landward north of 25° 10'N to form the feature known as Howell Hook (Holmes 1981). Samples dredged from the surface reveal that the reef consists, at least in part, of the type of coralline algae that typically caps reefs during the climax stage of growth (Holmes 1985). The reef is partially exposed under a very thin sand veneer and is colonized by corals, crinoids, sponges, and other sessile epifauna (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1985). The lower reef crests at a water depth of about 200 m and forms a 40-m-high scarp (Holmes 1981). Both reef features abruptly turn eastward at about 25° 50'N and are buried by the Late Pleistocene, outer shelf banks that rim the southern Straits of Florida (Shinn et al. 1977).

The shelf-edge banks and reefs trend east-west along the southern edge of the margin. In general, banks become progressively deeper to the west (Holmes 1981). The constructional material of each bank is unique. The easternmost bank, the Marquesas Keys, is composed of *Halimeda* sands that rest on a Pleistocene topographic high (Shinn et al. 1982). To the west, a dissected platform forms the Dry Tortugas and Tortugas Bank complex. Both the Marquesas and Dry Tortugas are currently being constructed by various massive and branching hermatypic corals that form fringing reefs around the islands (Shinn et al. 1977). Farther to the west are slightly elevated banks consisting of a fused pavement of coralline algae, sponges, and growths of plate corals (Holmes 1985). No information is available on the ages of the deeper banks; however, dredged material appears very similar to that of the Pleistocene foundation of the Dry Tortugas region (Holmes 1981). Surface sediments on the Straits of Florida side, and the crests of the Dry Tortugas banks consist of a veneer of sand (Davis and O'Neill 1979). The region immediately north of the banks is covered by silt-sized material (Holmes 1981).

The Southwest Florida upper continental slope grades gently into deeper water at <1° gradient. The shelf-slope break is a rather arbitrary division along this part of the margin, as there is no discernible break in slope (Brooks 1986). A thick accumulation of relatively Recent sediments occupies the upper slope between the Florida Canyon System to the west and the Pourtales Terrace to the east. Sediments are predominantly

sand-sized at the shelf edge and become finer in a seaward direction. They consist principally of a combination of shallow-water-derived and deepwater-derived carbonate detritus rich in shallow-water benthic molluscs and forams, and planktonic pteropods and forams. Shallow-water sediments are interpreted to be derived from the shallow shelf surface to the north (Brooks and Holmes 1989). Shallow-water-derived sediments are more like those from the shelf interior behind the shelf-edge banks rather than the adjacent banks themselves (Brooks 1986). High-resolution seismic reflection data show that the shelf margin is currently prograding in a seaward direction, presumably by continued off-shelf transport of shallow-water material, and deposition of this material on the upper slope along a seaward advancing front. The Florida Canyon System, on the western boundary of this sediment front, is actively eroding headward (to the northeast), as upper slope sediments collapse into the canyon. Presumably, upper slope sediments are eventually transported to the base of the slope, via the canyon, where they are deposited as turbidites or other gravity-flow deposits. The Pourtales Terrace, on the eastern margin of the sediment front, is a Miocene phosphatic limestone. It is currently being buried by eastward prograding sediments of the upper slope unit. This eastward trending sediment drift is interpreted to be a response to the strong eastward flowing Florida Current, which is the dominant physical process operating in the southern Straits of Florida.

The nearshore zone of the Southwest Florida shelf, extending from Cape Sable to Cape Romano (**Figure 2.1**), exhibits a variety of configurations and modern sediment characteristics, which are primarily a reflection of different environmental conditions. Cape Sable is considered the coastal boundary between Florida Bay and the West Florida shelf. Roberts et al. (1977) described Cape Sable as being a regionally distinct complex of sedimentary environments, representing a transition between the quartz-rich beaches and barrier islands of West Florida and the classical carbonate reef/back reef environments of the Keys. Seven sedimentary environments have been described for the modern Cape Sable complex (Roberts et al. 1977):

(1) **Beach ridges and beaches** characterize the ridge-and-swale topography of the three distinct cuspate features of Cape Sable (Roberts et al. 1977). Sediments consist almost entirely of sand-sized calcium carbonate, composed primarily of molluscan shell debris (Gebelein 1977; Roberts et al. 1977). Non-carbonate sedimentary components consist of siliceous sponge spicules with minor amounts of quartz and siliceous pollen grains (Roberts et al. 1977). Locally, exposed beach sand becomes indurated, producing an extremely hard, shelly limestone (Roberts et al. 1977).

(2) **Mangrove swamps** occur immediately behind the capes and beaches. Sediments consist of extremely fine-grained, dark carbonate muds with a high percentage of organic matter and light-colored, silt-sized shell debris (Roberts et al. 1977).

(3) **Tidal flats** are essentially shallow, intertidal basins bordered by mangroves. Sediments are composed of homogenous carbonate muds with few shell fragments (Roberts et al. 1977).

(4) **Lake Ingraham** is a shallow, protected, tidally-dominated lake located landward of the capes. Sediments consist of modern marine muds overlying freshwater carbonates. Modern muds are derived principally from *Penicillus* spp. and other aragonite-producing algae (Roberts et al. 1977). Sediments are structureless, as they are completely burrowed by benthic organisms.

(5) Supratidal plains with relict shoreline features lie along the inland shores of Lake Ingraham. Sediments are elevated above the range of normal tides and slope gently landward. Sediments are similar to the low-carbonate mudbanks that border the present shoreline of Florida Bay. They are interpreted to have formed by overbank sedimentation during storms. Layers of coarse silt- and fine sand-sized sediments are interpreted to represent these storm layers. In general, sediments are muddy and contain a high proportion of silt-sized aragonite and low-magnesium calcite derived from the fragmentation of mollusc shells (Roberts et al. 1977).

(6) Inland ponds and lakes occur landward of the supratidal plains. They are shallow and are dry during periods of little rainfall. Sediments consist of a dark brown, organic-rich carbonate mud. Sediments are marine, being totally reworked by benthic organisms (Roberts et al. 1977).

(7) Peat-forming brackish and freshwater swamps and marshes lie inland from the Cape Sable complex. This part of the complex has had limited access to Florida Bay since the 1940s when a canal was constructed (Roberts et al. 1977). Sediments are highly organic, with a considerable amount of molluscan shell debris. In addition, prolific communities of calcareous algae produce thin deposits of aragonite-rich mud (Roberts et al. 1977).

In summary, the Cape Sable complex is composed of a regionally distinct complex of sedimentary environments. Each individual environment has its own suite of faunal and sedimentary characteristics. Storms and frequency of tidal inundation are primary controls on modern sedimentation patterns, as well as the modern configuration as a whole (Gebelein 1977; Roberts et al. 1977).

Between Cape Sable and Cape Romano (**Figure 2.1**) lies the transition zone between quartz-dominated sediments and purely carbonate sediments. The gradient is very low (approximately 0.02°), as is the physical energy (Davis and Klay 1989). Surface sediments show a gradual trend in both composition and texture, from Gullivan Bay (just east of Cape Romano) southward. There is also a distinct difference between the coastal sediments within the inner 5 km (2.7 nmi), and those farther seaward. Grain size and calcium carbonate content increase to the south and away from the coast (Davis and Klay 1989). Cape Romano represents the southern limit of the quartz-dominated barrier island system. Immediately south of Cape Romano is a sand ridge complex that consists of several east-west trending, parallel sediment bodies. They display up to 4 m of relief, reach up to 10 km (about 5 nmi) in length, and are approximately 1 km (0.5 nmi) wide. These sand bodies, known as the Cape Romano Shoals, are dominated surficially by quartz sand and scattered shell (Tanner et al. 1963; Davis and Klay 1989). Ridge surfaces are characterized by well-sorted quartz sand, with minor amounts of biogenic gravel. Troughs contain more mud and gravel. Sand bodies are covered with bedforms ranging from ripples to sand waves (Davis and Klay 1989). Shoals may have formed by the southerly longshore drift system that contributes sand, in combination with tidal and wave activity (Holmes and Evans 1963; Tanner et al. 1963).

Gullivan Bay, located between the Cape Romano Shoals and Ten Thousand Islands, contains a large percentage of mud. This may be due to the relatively low physical energy and close proximity to a potential source in the Ten Thousand Islands (Holmes and Evans 1963; Davis and Klay 1989). Tanner et al. (1963) also pointed out that quartz sand is spread over the floor of Gullivan Bay as it is swept around the south end of the Cape Romano Shoals.

The Ten Thousand Islands region (**Figure 2.1**), located landward of Gullivan Bay, consists of low-relief, mangrove-capped oyster bars and vermetid worm reefs, separated by shallow bays or tidal channels. The islands form a band about 4 to 6 km (2 to 3 nmi) in width and about 40 km (22 nmi) in length. Mangrove peat is the typical sediment type, accumulating on all islands. Soft, organic-rich, shelly muds are currently accumulating within bays, except in more open bays where increased wave and current action produce shelly, quartz-rich sediments. Seaward, subtidal sediments become progressively sandier, and skeletal lags have developed in high-energy tidal channels. In general, gradients in sediment composition, as well as faunal assemblages, are a function of salinity, wave and current energy, biological sediment production, and proximity to quartz sand sources (Parkinson 1987).

Because environments are so diverse on the Southwest Florida continental margin, sediment distribution patterns and processes/controls on these patterns are highly variable. Throughout most of the margin, biogenic production of carbonate sediments may be the most direct regulator because of the predominance of carbonate sediments. On the open margin, physical processes are a major influence on sediment distribution and overall morphology of the margin. Processes such as storms associated with frontal systems, intrusion of the Loop Current (or associated phenomena) onto the shelf, and tidal currents are instrumental in transporting sediments southward across the shelf surface (Neurauter 1979; Holmes 1981) and eventually onto the upper slope where they are deposited along a seaward-advancing sediment front (Brooks and Holmes 1989). In more protected portions of the shelf, such as the Cape Sable complex and the Ten Thousand Islands area, it seems that each sedimentary environment responds to a particular set of physical conditions. In both areas, however, tidal processes have been reported to be a major influence (Roberts et al. 1977; Parkinson 1987). Sediment distribution patterns in specific areas such as the Cape Romano Shoals are a direct response to a combination of physical processes. The Cape Romano Shoals, as pointed out previously, are controlled by a combination of long-shore drift, tides, and wave activity (Holmes and Evans 1963; Tanner et al. 1963; Davis and Klay 1989). The delicate combination of these processes is responsible for maintaining this modern configuration.

GEOLOGY IN RELATION TO PETROLEUM EXPLORATION

Production Potential

Commercial hydrocarbon accumulations have not been discovered offshore in South Florida and the Straits of Florida region, but minor production has been occurring in peninsular South Florida. These small fields produce from the carbonate Sunniland reservoirs in the South Florida Basin (**Figure 1.1**), and the oil and gas may have originated from carbonate source rocks. According to Attilio and Blake (1983), Amato et al. (1986), Faulkner and Applegate (1986), and Montgomery (1987), the South Florida Basin has promising petroleum potential. Multiple trapping possibilities exist overlying a thick sedimentary section, but to date, the Sunniland Trend is the only producing zone discovered.

In addition to the Sunniland Formation, other horizons showing petroleum potential include the Dollar Bay, Lake Trafford, Pumpkin Bay, Bone Island, and Wood River Formations, as well as the Brown Dolomite zone of the Lehigh Acres Formation (Winston 1969; Faulkner and Applegate 1986; Montgomery 1987). Amato et al. (1986) also cited the Corkscrew Swamp, Rookery Bay, Gordon Pass, Marco Junction, and Rattlesnake Hammock Formations as having petroleum potential.

The Lower Cretaceous Dollar Bay Formation is considered the youngest unit with significant hydrocarbon potential. Numerous shows of oil have been reported (Montgomery 1987), mostly from the eastern part of the Basin. The Dollar Bay Formation consists principally of limestone, with localized "islands" of porous dolomite. Reservoir quality within the dolomite seems quite good, with porosities of over 20% reported from the Florida Keys area. Dolomite "islands" would be the most likely site for petroleum accumulation (Montgomery 1987).

The Sunniland Formation remains the sole producing horizon in South Florida. To date, production occurs along a well-defined, but continuous trend, approximately 250 km (135 nmi) long, 20 km (11 nmi) wide, and lying at depths of 3,500 to 3,600 m (Montgomery 1987). The trend lies onshore in Southwest Florida (**Figure 1.1**). At present, the consensus among experts is that numerous fields in the Sunniland Trend remain to be discovered (Montgomery 1987).

The Lower Cretaceous Brown Dolomite (Lehigh Acres Formation) is predicted to be the second interval to support major oil discoveries in the region (Applegate 1987; Montgomery 1987). It occurs approximately 300 m below the Sunniland Formation in the South Florida Basin. The best potential probably lies offshore in the central and western portion of the basin (Montgomery 1987).

The Pumpkin Bay Formation is considered the thickest and deepest interval in the South Florida Basin with significant reservoir potential (Montgomery 1987). Oil shows have been reported onshore in Southwest Florida, but the best reservoir potential is considered to be offshore in the most central portions of the basin. Here, the formation is projected to thicken to around 450 m and to reach depths of 4,500 m or more (Montgomery 1987).

The Wood River Formation, in the lowermost portion of the Mesozoic section, has one reported good show and minor production of gas (Montgomery 1987). The unit consists of limestone and dolomite overlying a basal clastic section of nonmarine or marginal sands and shales. Reservoir quality has not been studied (Montgomery 1987).

In general, the thick carbonate section within the South Florida Basin is considered to have good potential for petroleum accumulation. Initial estimates of eventual discoveries are now being formulated. For example, most experts agree that new discoveries within the existing Sunniland Trend are fairly certain within the next few years. Many also concur that the potential in other parts of the basin may be much greater than previously believed (Montgomery 1987). At present, however, more systematic studies are required to more accurately determine reservoir potential.

Additional information on petroleum potential of the South Florida Basin is presented in **Chapter 12** in connection with a discussion of oil and gas operations.

Geohazards and Constraints

Potential geohazards and constraints to operations in the South Florida study area are in the form of carbonate buildups, karst topography, channelization, seafloor instability, sediment movement, and faulting. Carbonate buildups include both active and inactive reef complexes associated with the Reef Tract seaward of the Florida Keys and the Marquesas Keys and Dry Tortugas to the west. Locations and morphologies have been fairly well documented. A shallow, buried reef complex has been described, separating the inner and outer Southwest Florida shelf at water depths of approximately 70 to 90 m (Holmes 1985). The complex is approximately 10 km (5 nmi) wide as it forms a series of seaward-trending steps. It is partially exposed in places, and supports

a live bottom community (see **Chapter 5**). Another reef complex occupies the shelf edge in 130- to 200-m water depths (Holmes 1985). The reef is partially exposed, and contains pinnacles extending 1 to 5 m above the seafloor. As with the mid-shelf complex, the outer system supports a live bottom assemblage.

Karst topography is prevalent throughout the study area. Solution features known as pockmarks have been reported on both the inner and outer West Florida shelf (Holmes 1985). Toward the middle shelf, these features are buried, presumably by sediments produced by the mid-shelf reef complex. Pockmarks are shallow depressions, ranging from <20 m to 2,000 m across. The Pourtales Terrace, cropping out at approximately 200-m water depths downslope from the Marquesas Keys, exhibits a very rugged and complex topography that is believed to be the result of carbonate solution (Jordan 1954). Karst has been identified in Florida Bay, but generally is considered to be relatively small scale (microkarst), occurring in the underlying Pleistocene limestone surface.

Channelization has not been well documented within the study area, but numerous buried channels have been identified to the north off the coasts of Naples, Ft. Myers, and Tampa Bay (Foote et al. 1983). Channels probably formed during lower stands of sea level as rivers traversed the shelf on their way to the sea. Channels appear to rest on a very strong acoustic horizon (Miocene surface) approximately 10 m below the seafloor. Another type of channelization is occurring in modern Florida Bay. Tidal and storm current activity is constantly modifying mudbank geometry and orientation and, therefore, the channels separating them.

Seafloor instability applies to continental slope environments where mass transport processes occur. The Southwest Florida upper slope adjacent to the southern Straits of Florida is an area of rapid sediment accumulation (Brooks and Holmes 1989). Pull-apart structures and associated down-slope compressional folds identified as creep have been reported at approximately 100-m depths (Brooks 1986a). Additionally, turbidites at the base of the slope and erosional gullies on the lower slope are interpreted to have formed by gravity-flow processes (Brooks and Holmes 1989). The head of the Florida Canyon System immediately to the west is actively eroding landward (Brooks 1986a). Material collapses into the canyon and is probably transported down-slope by gravity-flow processes. Few data have been gathered where the slope trends to the north, but similar types of processes are expected. The slope bordering the Keys is poorly documented. Slopes bordering other reef-rimmed carbonate platforms, however, undergo a variety of mass-wasting processes. Consequently, the slope seaward of the Keys may be expected to be similarly active. Triggering mechanisms for slope failure in the study area are probably a combination of sediment overloading and water current activity.

Sediment movement occurs throughout the study area, albeit in different forms. Sand movement has been documented on the outer West Florida shelf. Southerly oriented sand waves indicate transport in that direction (Neurauter 1979). Sands are mobilized and eventually transported off the shelf and deposited along the upper slope. Sands are probably transported principally in response to storm frontal systems that average every 5 to 10 days during winter. Sands and muds are transported eastward along the upper slope bordering the southern Straits of Florida. Sediments are progressively burying the Pourtales Terrace from west to east (Brooks 1986a). Transport is interpreted to be a response to the strong, eastward-flowing Florida Current. Sand-sized and mud-sized sediments are mobilized and transported through narrow passes between the Keys in response to tidal currents (Enos 1977). The result is a series of tidal deltas that reflect not only tidal currents, but also wave energy, sediment supply, and water current conditions. Sands are mobilized along the inside of the Reef

Tract, principally by hurricanes and winter storms (Shinn et al. 1989). The direction of transport is a function of storm direction and location.

Faulting has been identified on the Southwest Florida shelf and slope (Foote et al. 1983). It is not known whether faulting is active at present, and even near-surface faults exhibit little or no surface expression. It is also questionable whether features identified on seismic records are indeed faults and not simply artifacts due to velocity anomalies.

Other potential constraints that may not have been documented but may be of importance include current scour and gaseous sediments. Many areas along the Straits of Florida are commonly scoured as the Florida Current progresses from the Gulf into the Atlantic (Brooks 1986a). Scour can result in slope instability, irregular topography, or sediment mobilization. Gaseous, and consequently internally unstable sediments, may be expected in regions of high organic productivity and very restricted circulation, as may occur in interior Florida Bay environments.

CONCLUSIONS

South Florida exhibits a wide variety of geologic environments. Some, like the Florida Keys/Reef Tract and to a lesser extent Florida Bay, have been studied in some detail; others such as the Southwest Florida margin, have received relatively little attention. Nevertheless, sufficient information was available from which to piece together the geologic framework for South Florida, and to provide a basis for subsequent discussions concerning petroleum activity in the study area.

In general terms, geologic information needs for South Florida are in two distinct forms. First is the simple need to fill geographic gaps. Second is the more complicated task of identifying processes controlling geologic development. From a management perspective, the identification of processes is probably the most valuable. An understanding of geologic processes will be useful for more accurately predicting how the environment will respond to outside influences (e.g., fluctuating sea level, storm events, anthropogenic activities).

To date, most of the data collected on South Florida have been descriptive in nature, especially for the poorly studied Southwest Florida margin. Process-related studies on the Florida Keys/Reef Tract and Florida Bay, although more numerous, have generally concentrated on a specific geographic area (e.g., a single basin in Florida Bay), resulting in a wide variety of environments described as being controlled by a distinct set of processes. This is especially true of Florida Bay, consisting of numerous separate basins, many of which have been described as developing in response to a combination of processes unique to each specific basin.

Notwithstanding, based upon the numerous studies performed in the study area, it is possible to cite the major processes most responsible for recent geologic development. Probably the overall most important process is fluctuating sea level. Glacially-induced sea level fluctuations during the Late Quaternary and, more recently, the Holocene sea level rise, have provided the framework for the Florida Keys and surrounding reefs, the shallow basins of Florida Bay, and even the relatively flat-lying Southwest Florida margin. In the shorter term, modern processes controlling development of the Florida Keys/Reef Tract include skeletal productivity that generates carbonate sediments, and physical processes such as high-energy waves and storm tides that mechanically redistribute sediments. Florida Bay also consists predominantly of carbonate sediments, and therefore, $CaCO_3$ productivity would have to be considered a major process responsible for development. In addition, tidal and storm-generated currents are controlling physical processes. Development of the Southwest Florida margin is

controlled to some extent by biological production of calcium carbonate, but the dominant controls are the physical processes operating on the shelf and upper slope, such as oceanic currents, tidal currents, and storm events. These processes are responsible for distributing sediments and generally shaping the entire area.

As pointed out above, information needs include filling geographic gaps as well as learning more specifically about the processes controlling geologic development. On the Southwest Florida margin, more studies should be aimed at identifying the processes and controls governing the modern shelf configuration, and how they relate to overall margin development. More detailed information should also be gathered over the slope environment, especially the thick, upper slope sediment accumulations. Investigations should be geared toward elucidating the causes and precise timing of slope processes such as deposition, erosion, and failure. Additionally, data need to be gathered in the critical shelf-slope transition zone for the purpose of determining how outer shelf and upper slope facies relate to one another, and to overall margin development.

Although detailed data exist on the Florida Keys and Reef Tract, relatively little is known about the adjacent slope environment. Investigations are needed to determine processes and controls on slope development, including slope stability. Specifically, a determination needs to be made as to how the slope compares with other reef-rimmed platform slopes (such as the Bahamas) as well as the immediately adjacent non-reef-rimmed slope along the Southwest Florida margin.

A major data gap identified from this study is in the zone between Florida Bay and the Southwest Florida shelf. Although data exist for the coast in the Cape Sable complex, no data have been identified seaward between, for example, Cape Sable and the Dry Tortugas. Detailed information needs to be gathered in order to determine how the transition between the two environments is made, not only on the surface but in the underlying limestone foundation. Once again, sediment distribution patterns and controlling processes need to be identified, as well as how they relate to the geologic development of the region of transition and South Florida carbonate platform as a whole.

In general, future research efforts should concentrate on the Southwest Florida margin and the Southeast Florida slope bordering the Florida Keys in order to reach the present level of understanding of the Keys/Reef Tract and Florida Bay. Special attention should be given to the Southwest Florida margin because petroleum production appears to have the highest potential in the offshore portion of the South Florida Basin. Investigations should be process-oriented, concentrating not only on description of environments, but also on processes governing facies changes and geologic development.

REFERENCES CITED

Amato, R. V., W. E. Sweet, G. M. Edson, C. J. O'Hara, D. M. Clark, and G. Pickens. 1986. *Regional geology and petroleum potential of the Straits of Florida Planning Area.* U.S. Department of the Interior, Minerals Management Service. Unpubl. manuscript.

Applegate, A. V. 1987. *The brown dolomite zone of the Lehigh Acres formation (Aptian) in the South Florida Basin--A potentially prolific producing horizon offshore.* Fla. Bur. Geol. Info. Circ. No. 104, Pt. II. Tallahassee.

Applegate, A. V., and J. M. Lloyd. 1987. *Part 1 - 1985 Florida petroleum production and exploration.* Fla. Geol. Surv. Info. Circ. No. 104.

Attilio, D. E., and B. Blake. 1983. Petroleum potential, exploration possibilities of S. Florida basin, Florida Keys. *Oil Gas J.*, 7 Nov. 1983:148-153.

Bathurst, R. C. 1975. *Carbonate sediments and their diagenesis.* New York: Elsevier.

Brooks, G. R. 1985. Cyclic deposition and erosion on the Southwest Florida continental slope: A response to high frequency sea-level fluctuations. *Bull. Geol. Soc. Am., Abstracts with Program.*

Brooks, G. R. 1986a. Recent continental slope sediments and sedimentary processes bordering a non-rimmed carbonate platform: Southwest Florida continental margin. Ph.D. diss., Univ. of South Florida, St. Petersburg.

Brooks, G. R. 1986b. *Rapid sedimentation on a modern carbonate slope - Southwest Florida continental margin.* Soc. Econ. Paleont. Mineral., Abstracts with Program.

Brooks, G. R., and C. W. Holmes. 1989. Recent carbonate slope sediments and sedimentary processes bordering a non-rimmed platform: Southwest Florida continental margin. In *Controls on carbonate platforms and basin development*, ed. P. D. Crevello, J. L. Wilson, J. F. Sarg, and J. F. Read, 259-272. Tulsa: Soc. Econ. Paleont. Mineral., Spec. Publ. No. 44.

Brooks, I. H., and P. P. Niiler. 1975. The Florida Current at Key West: Summer 1972. *J. Mar. Res.* 33:83-92.

Brunner, C. A. 1986. Deposition of a muddy sediment drift in the southern Straits of Florida during the Late Quaternary. *Mar. Geol.* 65:239-249.

Danek, L. J., and G. S. Lewbel, ed. 1986. *Southwest Florida shelf benthic communities study. Year 5 annual report.* OCS Study 86-0075. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Davis, R. A., and J. M. Klay. 1989. Origin and development of Quaternary terrigenous inner shelf sequences, Southwest Florida. *Trans. Gulf Coast Assoc. Geol. Soc.* 39:341-347.

Davis, R. A., and C. W. O'Neill. 1979. Morphodynamics of East Key, Dry Tortugas, Florida. In *Guide to sedimentation for the Dry Tortugas*, ed. R. B. Halley, 7-13. S.E. Geol. Soc. Publ. No. 21.

Doyle, L. J., G. R. Brooks, and J. Hebert. 1985. Submarine erosion and karstification on the West Florida continental margin: From disparate environments yield similar features. *Bull. Geol. Soc. Am., Abstracts with Program.*

Enos, P. 1977. Holocene sediment accumulations of the South Florida shelf margin. In *Quaternary sedimentation in South Florida*, ed. P. Enos and R. D. Perkins, 1-130. Geol. Soc. Am. Mem. No. 147.

Enos, P., and R. D. Perkins, ed. 1977. *Quaternary sedimentation in South Florida.* Geol. Soc. Am. Mem. No. 147.

Enos, P., and R. D. Perkins. 1979. Evolution of Florida Bay from island stratigraphy. *Bull. Geol. Soc. Am.* 90:59-83.

Environmental Science and Engineering, Inc., LGL Ecological Research Associates, Inc., and Continental Shelf Associates, Inc. 1987. *Southwest Florida shelf ecosystems study data synthesis report.* OCS Study MMS 87-0023. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Faulkner, B. M., and A. V. Applegate. 1986. Hydrocarbon exploration evaluation of the Pulley Ridge area, offshore South Florida Basin. *Trans. Gulf Coast Assoc. Geol. Soc.* 36:83-95.

Foote, R. Q., G. L. Shideler, C. W. Holmes, L. J. Doyle, L. M. Massingill, and R. H. Wells. 1983. *Summary report on the regional geology, petroleum potential, environmental considerations for development, and estimates of undiscovered recoverable oil and gas resources in the area of the proposed November 1985 oil and gas lease sale offering, eastern Gulf of Mexico.* New Orleans: U.S. Department of the Interior, Minerals Management Service.

Gebelein, C. D. 1977. *Dynamics of recent carbonate sedimentation and ecology, Cape Sable, Florida.* Leiden: E. J. Brill.

Ginsburg, R. N. 1956. Environmental relationships of grain size and constituent particles in some South Florida carbonate sediments. *Am. Assoc. Pet. Geol. Bull.* 40:2384-2427.

Ginsburg, R. N., ed. 1972. *South Florida carbonate sediments.* Miami: Univ. of Miami, Comparative Sedimentology Laboratory.

Gorsline, D. S. 1963. Environments of carbonate deposition, Florida Bay and Florida Straits. In *Shelf carbonates of the Paradox Basin*, 130-143. Durango, CO: Four Corners Geol. Soc. 4th Annual Field Conference.

Halley, R. B., ed. 1979. *Guide to sedimentation for the Dry Tortugas.* S.E. Geol. Soc. Publ. No. 21.

Harrison, R. S., and M. Coniglio. 1985. Origin of the Pleistocene Key Largo Limestone, Florida Keys. *Bull. Can. Pet. Geol.* 33:350-358.

Hoffmeister, J. E. 1974. *Land from the sea.* Miami: Univ. Miami Press.

Hoffmeister, J. E., and H. G. Multer. 1968. Geology and origin of the Florida Keys. *Bull. Geol. Soc. Am.* 79:1487-1502.

Holmes, C. W. 1981. *Late Neogene and Quaternary geology of the southwestern Florida shelf and slope.* U.S. Geol. Survey Open File Rep. No. 81-79.

Holmes, C. W. 1985. Accretion of the South Florida platform, Late Quaternary development. *Am. Assoc. Pet. Geol. Bull.* 69:149-160.

Holmes, C. W., and R. G. Evans. 1963. Sedimentology of Gullivan Bay and vicinity, Florida. *Sedimentology* 2:189-206.

Hudson, J. H. 1985. Growth rate and carbonate production in *Halimeda opuntia*, Marquesas Keys, Florida. In *Paleontology: Contemporary research and applications*, ed. D. F. Toomey and M. H. Nitecki, 257-263. Berlin: Springer-Verlag.

Jordan, G. F. 1954. Large sinkholes in Straits of Florida. *Am. Assoc. Pet. Geol. Bull.* 38:1810-1817.

Kick, R. M. 1981. Carbonate sediments from Peterson Key Bank, Florida Bay. M.S. thesis, Univ. of South Florida, Tampa.

Klitgord, K. D., P. Popenoe, and H. Shouten. 1984. Florida: A Jurassic transform plate boundary. *J. Geophys. Res.* 89:7753-7772.

Krivoy, H. L., and T. E. Pyle. 1972. Anomalous crust beneath West Florida shelf. *Am. Assoc. Pet. Geol. Bull.* 56:107-113.

Lee, T. N. 1989. *Physical oceanography literature review of the Straits of Florida and eastern Gulf of Mexico.* Unpubl. manuscript.

Lidz, B. H., D. M. Robbin, and E. A. Shinn. 1985. Holocene carbonate sedimentary petrology and facies accumulation, Looe Key National Marine Sanctuary, Florida. *Bull. Mar. Sci.* 36:672-700.

Manker, J. P., and G. M. Griffin. 1977. Source and mixing of insoluble clay minerals in a shallow water carbonate environment - Florida Bay. In *Carbonate Rock Environments*, ed. H. G. Multer. Dubuque: Kendall-Hunt.

Marszalek, D. S., G. Babashaff, M. R. Noel, and D. R. Worley. 1977. Reef distribution in South Florida. In *Proceedings, Third International Coral Reef Symposium*, 223-229. Miami: Univ. of Miami.

Martin, D. W. 1984. Clastic to carbonate transitions - a modern example: The West Florida continental shelf. M.S. thesis, Univ. of South Florida, St. Petersburg.

Martin, R. G. 1976. Geologic framework of northern and eastern continental margins, Gulf of Mexico. In *Beyond the shelf break*, ed. A. Bouma, C. Moore, and J. Coleman, A1-A28. New Orleans: Am. Assoc. Pet. Geol. Short Course.

McCallum, J. S., and K. W. Stockman. 1972. Water circulation, Florida Bay. In *South Florida carbonate sediments*, ed. R. N. Ginsburg, 11-14. Miami: Univ. of Miami.

Merriam, D. F. 1988. Some recent developments in the study of Florida Bay geology. *The Compass* 65:157-175.

Merriam, D. F. 1989. Overview of the geology of Florida Bay: Review of recent developments. *Bull. Mar. Sci.* 44(1):519.

Merriam, D. F., S. Sengupta, and P. J. Zimmerman. 1985. Regional variation of water-chemical properties affecting the water/sediment interface in Florida Bay. *The Compass* 62:106-115.

Merriam, D. F., C. E. Sorensen, and R. V. Jenkins. 1987. Modern carbonate sediments in Shell Key Basin, Florida Bay. In *Symposium on South Florida geology*, ed. F. Maurrasse, 73-90. Miami: Miami Geol. Soc. Mem. No. 3.

Milligan, D. B. 1962. Marine geology of the Florida Straits. M.S. thesis, Florida State Univ.

Mitchell-Tapping, H. J. 1986. Exploration petrology of the Sunoco Felda Trend of South Florida. *Trans. Gulf Coast Assoc. Geol. Soc.* 36:241-256.

Montgomery, S. L. 1987. Success and sensibility in South Florida. *Pet. Front.* 4:1-52.

Muller, G., and J. Muller. 1977. Mineralogisch-sedimentpetrographische and chemische untersuchungen an einem bank-sediment (Cross Bank) der Florida Bay, U.S.A. In *Carbonate rock environments*, ed. H.G. Multer, 71-72. Dubuque: Kendall-Hunt.

Multer, H. G., ed. 1977. *Carbonate rock environments*. Dubuque: Kendall-Hunt.

Neurauter, T. W. 1979. Bedforms on the West Florida shelf as detected with side scan sonar. M.S. thesis, Univ. of South Florida, St. Petersburg.

O'Neill, C. W. 1976. Sedimentology of East Key, Dry Tortugas, Florida. M.S. thesis, Univ. of South Florida, St. Petersburg.

Parkinson, R. W. 1987. Holocene sedimentation and coastal response to rising sea level along a subtropical low energy coast, Ten Thousand Islands, Southwest Florida. Ph.D. diss., Univ. of Miami.

Perkins, R. D. 1977. Depositional framework of Pleistocene rocks in South Florida. In *Quaternary sedimentation in South Florida*, ed. P. Enos and R. D. Perkins, 131-198. Geol. Soc. Am. Mem. No. 147.

Price, W. A. 1967. Development of the basin-in-basin honeycomb of Florida Bay and the northeastern Cuban lagoon. *Trans. Gulf Coast Assoc. Geol. Soc.* 17:368-399.

Pyle, T. E., W. R. Bryant, and J. W. Antoine. 1974. Structural framework of the West Florida continental shelf and recommendations for further research. In *Procedures of marine environment implications of offshore drilling eastern Gulf of Mexico*, ed. R. E. Smith, 97-109. St. Petersburg: State Univ. Syst. Inst. Oceanogr.

Quinn, T. M., and D. F. Merriam. 1988. Evolution of Florida Bay islands from a supratidal precursor: Evidence from westernmost Bob Allen Key and Sid Key. *J. Geol.* 96:375-381.

Richardson, W. S., W. J. Schmitz, and P. P. Niiler. 1969. The velocity structure of the Florida Current from the Straits of Florida to Cape Fear. *Deep-Sea Res.* 16:225-231.

Roberts, H. H., T. Whelan, and W. G. Smith. 1977. Holocene sedimentation at Cape Sable, South Florida. *Sediment. Geol.* 18:25-60.

Roberts, H. H., L. J. Rouse, N. D. Walker, and J. H. Hudson. 1982. Cold-water stress in Florida Bay and northern Bahamas: A product of winter cold-air outbreaks. *J. Sediment. Petrol.* 52:145-156.

Robinson, R. B. 1967. Diagenesis and porosity development in recent and Pleistocene oolites from South Florida and the Bahamas. *J. Sediment. Petrol.* 37:355-364.

Schlager, W., R. T. Buffler, D. Angstadt, and R. Phair. 1984. Geologic history of the southeastern Gulf of Mexico (draft). *Initial Rep. Deep-Sea Drill. Proj. - Leg 77.*

Scholl, D. W. 1966. Florida Bay: A modern site of limestone formation. In *Encyclopedia of oceanography*, ed. R. W. Fairbridge, 282-288. New York: Reinhold.

Scholl, D. W. 1977. Florida Bay: A modern site of limestone formation. In *Carbonate rock environments*, ed. H.G. Multer, 66-71. Dubuque: Kendall-Hunt.

Shinn, E. A. 1972. Recent dolomite, Sugarloaf Key. In *South Florida carbonate sediments*, ed. R. N. Ginsburg, 62-67. Miami: Univ. of Miami.

Shinn, E. A. 1988. The geology of the Florida Keys. *Oceanus* 31:46-53.

Shinn, E. A., J. H. Hudson, R. B. Halley, and B. Lidz. 1977. Topographic control and accumulation rate of some Holocene coral reefs: South Florida and Dry Tortugas. In *Proceedings, Third International Coral Reef Symposium*, 1-7. Miami: Univ. of Miami.

Shinn, E. A., J. H. Hudson, D. M. Robbin, and B. Lidz. 1981. Spurs and grooves revisited: Construction versus erosion Looe Key reef, Florida. In *Proceedings, Fourth International Coral Reef Symposium*, 475-483. Manila, Philippines.

Shinn, E. A., C. W. Holmes, J. H. Hudson, D. Robbin, and B. H. Lidz. 1982. Non-oolitic, high energy carbonate sand accumulation: the quicksands of Southwest Florida Keys. *Am. Assoc. Pet. Geol., Abstracts with Program.*

Shinn, E. A., B. H. Lidz, J. L. Kindinger, J. H. Hudson, and R. B. Halley. 1989. *A field guide: Reefs of Florida and the Dry Tortugas*. Washington, DC: 28th International Geological Congress.

Sorensen, C. E. 1985. Quantitative analysis of the carbonate sediments in Shell Key basin, Florida Bay. *The Compass* 62:97-105.

Stewart, H. B. 1962. *Oceanographic cruise report, U.S. coast and geodetic survey ship Explorer - 1960.* Washington, DC: U.S. Department of Commerce.

Stockman, K. W., R. N. Ginsburg, and E. A. Shinn. 1967. The production of lime mud by algae in South Florida. *J. Sediment. Petrol.* 37:633-648.

Tanner, W. F., R. G. Evans, and C. W. Holmes. 1963. Low-energy coast near Cape Romano, Florida. *J. Sediment. Petrol.* 33:713-722.

Tyson, R. G. 1981. Sediments of a Florida Bay basin. M.S. thesis, Univ. of South Florida, Tampa.

Winston, G. O. 1969. A deep glimpse of West Florida's platform. *Oil Gas J.* 62:2290-2307.

Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1983. *South Florida shelf ecosystems study, marine habitat atlas, Vol. 2.* New Orleans: U.S. Department of the Interior, Minerals Management Service.

Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1985. *Southwest Florida shelf ecosystems study - Year 2.* New Orleans: U.S. Department of the Interior, Minerals Management Service.

CHAPTER 3
ENVIRONMENTAL CHEMISTRY

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INTRODUCTION

South Florida's reputation for clear, pristine waters is a major factor in its popularity as a recreational site for both tourists and residents. Because of the area's low population density, low level of industrial development, and lack of major rivers, concentrations of chemical contaminants are generally low. However, water chemistry problems have been identified, including hypersalinity due to evaporation and limited freshwater discharge into Florida Bay (Robblee et al. 1989), introduction of pesticides from agricultural drainage (Skinner and Jaap 1986; Skinner 1988a), and nutrient enrichment of groundwaters and nearshore waters due to on-site sewage disposal in the Florida Keys (Lapointe and O'Connell 1988). The nutrient problem is of special concern because nutrient inputs could alter the ecological balance of nearshore communities such as coral reefs and seagrass beds (Lapointe and O'Connell 1988; Lapointe 1989).

This chapter focuses on trace metals and hydrocarbons, because their concentrations could be directly affected by offshore oil and gas drilling and production in the study area. Both trace metals and hydrocarbons are present in South Florida waters from natural sources and existing human inputs. Drilling discharges would introduce some trace metals (such as barium) that are currently present at very low concentrations (see **Chapter 13**). Parts of the study area already contain high concentrations of pelagic tar from tanker discharges; oil spills and routine production discharges could introduce additional petroleum hydrocarbons.

TRACE METALS

B. J. Presley

Trace Metal Sources

Trace metals have both natural and anthropogenic sources. Continental rocks, soils, and organisms have variable concentrations of trace metals, some of which are released during weathering, decomposition, and destruction of the parent materials. Released trace metals are transported from continents to oceans, both in dissolved form and associated with particles of various sizes. In addition to these natural sources of trace metals on the continents, natural oceanic sources might, in some cases, supply significant amounts of trace metals to nearshore areas. Human activities, both on the continent and in the sea, can also significantly influence the nearshore flux of trace metals.

For most nearshore environments, most trace metals will come from the nearby land. However, seawater may be a more important source for areas adjacent to limestone terrains with little industrial development, such as the Florida Keys. Marine sources of trace metals such as undersea volcanos and hydrothermal vents, manganese nodules, etc. are not commonly found in this area. Human activities in the marine environment, such as dredging, construction, shipping, and oil and gas operations, must also be considered.

In describing land sources of trace metals, a first consideration is their transport to the ocean. Trace metals can be transported by rivers, the atmosphere, or through human activities.

Rivers

Rivers are the main pathway by which both natural and pollutant trace metals reach the coastal ocean in most parts of the world. Garrels and Mackenzie (1971) estimated that rivers account for 90% of the total seaward transport of dissolved and suspended material. The Gulf of Mexico receives about 69% of the total dissolved material (Leifeste 1974) and 77% of the total suspended solids (Curtis et al. 1973) transported to the ocean from the continental U.S. The Mississippi and Atchafalaya Rivers account for about 86% of all U.S. riverine transport to the Gulf of Mexico. To characterize the Mississippi River input is, therefore, sufficient to describe a large percentage of the input of continental material to the Gulf of Mexico. The Mississippi River probably has little effect on the Florida Keys area, however, as its flow is mainly directed westward and in any case is only about 1/800th that of the Loop Current which affects the eastern Gulf.

Atmosphere

Numerous studies of atmospheric transfer of trace metals from continents to oceans have been recently conducted (e.g., Buat-Menard 1986). It is generally recognized that atmospheric transport dominates over riverine transport for open ocean areas far from land. For some metals (such as lead) that have been abundant in automobile exhaust, atmospheric transport dominates even in coastal regions, especially near population centers. Other processes, such as cement manufacturing and coal burning, can also add large amounts of some trace metals to the atmosphere. For these metals, the atmosphere can be a significant transport pathway to the coastal ocean, especially in areas remote from large rivers. Church et al. (1982) suggested that atmospheric sources of several trace metals are as great as riverine sources for the Mid-Atlantic coast (Delaware area) and Windom (1980) reached similar conclusions about the Georgia coast. Unfortunately, no data are available on atmospheric inputs of trace metals to the

Florida Keys area, but the input could be significant due to large power plants and other industry in the Miami area, which could release aerosols rich in arsenic, cadmium, copper, selenium, zinc, and perhaps other metals.

Human Activities

Human activities, both on land and at sea, are capable of greatly disturbing the marine environment. Activities such as mining, smelting, manufacturing, energy production, and agriculture mobilize trace metals on the land, which results in enhanced transfer to the sea. Rapid population increases over the past 10 years in South Florida and the Florida Keys are a major concern because wastes generated on land have the potential to pollute the marine environment.

A number of human activities are potential sources of direct addition of trace metals to the study area. For example, ocean dumping of industrial wastes from ships or barges has been a major concern in some places. Ocean waste disposal through industrial outfalls is closely related to ocean dumping. In some parts of the country, some industrial waste pipelines discharge directly into estuarine or marine waters. These are regulated by the U.S. Environmental Protection Agency (EPA) but can, nevertheless, degrade the marine environment, especially in view of the difficulty of monitoring compliance with EPA permits. The power plant at Turkey Point (in southern Biscayne Bay) is one of the few industrial outfalls with a potential to affect the study area, but more data are needed on industrial and municipal discharges in the area.

In addition to ocean dumping and pipeline discharges of wastes, two other human activities potentially affect trace metal distributions in the study area: (1) oil and gas activities, and (2) dredging to create and maintain navigable channels. The latter has caused concern in the South Florida area due to building of numerous marinas and small boat channels and the increased small boat traffic. Petroleum exploration, development, and production operations are of concern because a number of associated activities could affect trace metal levels in the area--for example, transporting and constructing drilling platforms, building pipelines, etc. However, the two activities that have received the most attention are disposal of drilling fluids and cuttings, and disposal of produced water. These discharges are discussed briefly below, and in more detail in **Chapter 13.**

Drilling fluids (also known as drilling muds) are essential to oil and gas drilling. Circulation of drilling fluids through the well cools the drill bit, removes cuttings, coats the borehole to prevent fluid loss, controls downhole pressure, and performs other functions (National Research Council [NRC] 1983). Drilling fluids are essentially made from fresh water or seawater and bentonite (montmorillonite) clay. However, many chemicals are added to the fluids to perform specific functions; as a result, over 1,000 brand name additives are on the market. By far the most common additive is barite ($BaSO_4$), which is added to increase drilling fluid weight. This compound can amount to 90% or more of the dry weight of typical drilling fluids. Other common additives include chrome lignosulfonate, lignite, and sodium hydroxide. All of these additives may contain trace metals; therefore, depending on the amount and nature of additives, drilling fluids contain variable concentrations of trace metals.

Another substance discharged to the ocean in large amounts is produced water (also known as formation water) that is produced with petroleum and that must be separated from it during offshore production operations. Over the lifetime of a typical production well in the Gulf, the amount of produced water discharged can be as much as eight times the amount of oil extracted (EPA 1987). These discharges could add significant amounts of some trace metals to seawater, but the chemical composition of produced

water is not well known. The discharges are typically enriched in barium, boron, bromine, fluorine, iron, lithium, manganese, and strontium (Collins 1975), but the concentrations of rarer and more toxic trace metals, such as cadmium and lead, are not well known. If produced water mixes rapidly with a large volume of seawater, then even toxic metals would be rapidly diluted to harmless concentrations, unless the metals were initially present in very high concentrations, which seems unlikely. Nevertheless, more study of the nature and fate of produced water is needed.

Trace Metal Distribution

Dissolved in Water

Most reported concentrations of trace metals dissolved in seawater are 10 to 1,000 times higher than values reported in recent, high quality data sets. Bruland (1983) reviewed recent dissolved trace metal data and discussed problems with earlier data. He pointed out that only within the past 10 years have sets of dissolved trace metal data for seawater been obtained that conform to known physical and biological oceanographic parameters. For example, concentrations of a number of metals have now been shown to correlate well with nutrient concentrations, whereas in older literature no correlations between trace metals and other oceanographic parameters could be found. It should also be noted that only a few investigators in the world have produced these "oceanographically consistent" dissolved trace metal data sets, and even recent data from most investigators should be viewed with extreme skepticism. Researchers who are now able to produce high quality dissolved trace metal data possess no unusual skills or equipment unavailable to other investigators. They simply recognize the need for extreme care in sampling, storing, and analyzing seawater, and they use clean-room procedures throughout the process.

Unfortunately, few seawater samples from the South Florida shelf have been analyzed for dissolved trace metals with the care required to lend confidence to the data. Data that are almost certainly of high quality have, however, been reported by Edward Boyle and his co-workers. Boyle is one of the most respected and experienced seawater analysts in the world. Boyle et al. (1984) reported on a set of approximately 50 surface samples collected along a cruise track extending from Miami, around the tip of Florida, and across the Gulf of Mexico to near Bay Saint Louis, Mississippi. Only three or four of the stations were in the South Florida study area but a number of others were just outside the area. The cruise track crossed the Loop Current and a warm core ring. In spite of these different water masses and the long cruise track, there were almost no differences in surface seawater concentrations of cadmium, copper, and nickel (the only metals determined) anywhere in the open Gulf. The open Gulf surface samples had concentrations of 0.0005 μg/L for cadmium, 0.082 μg/L for copper, and 0.11 μg/L for nickel--values much lower than those reported by previous investigators (e.g., Slowey and Hood 1971). However, the surface samples collected a few kilometers off the Mississippi coastline had higher values, averaging 0.02 μg/L for cadmium and 0.5 μg/L each for copper and nickel. These coastal concentrations, obtained by Shiller and Boyle (1983) from samples collected in April 1981, are similar to values obtained by Shiller and Boyle (1983) from samples collected farther west, in the Mississippi River plume. Thus, concentrations of these three metals are fairly constant in surface coastal Gulf of Mexico water. Although the concentrations are considerably higher than open Gulf values, they are nevertheless much lower than values reported by most other investigators.

These lower values are supported by data from Spencer et al. (1982), who sampled a single station in the Straits of Florida. They reported concentrations of 0.005 μg/L for cadmium, 0.2 μg/L for copper, 0.02 μg/L for lead, and 0.012 μg/L for zinc. Spencer et

al. (1982) found dissolved trace metal concentrations at a station in the Sargasso Sea similar to those at the Straits of Florida location. Both data sets are similar to surface ocean values from elsewhere as summarized by Bruland (1983). Thus, there is no reason to believe that open ocean concentrations of any trace metal would be higher than average in the South Florida study area. Concentrations in shallow-water bays and lagoons are less certain, and very high values have been reported. For example, Chesher (1975) studied effluents from a large desalination plant in Safe Harbor on Stock Island in the Florida Keys. He found several parts per million copper, nickel, and iron in the effluent and high values in the receiving water. Skinner (1988b) reported 5 μg/L arsenic, <1 μg/L cadmium, and 0.5 μg/L mercury, but 5 μg/L lead and 5 and 16 μg/L copper in the Marvin D. Adams Waterway and Largo Sound. It is impossible to judge the significance of these reported high dissolved trace metal concentrations because the methods of analysis are not well documented in the reports.

The role of diffusion from sediment pore water in controlling trace metal concentrations in overlying coastal seawater has been much discussed, but not enough work has been done to verify its importance for most metals. It seems clear that the phenomenon is important for manganese, which exists in sediments as an oxide that is easily reduced to the soluble Mn^{+2} form. Trefry and Presley (1982) calculated that manganese was diffusing from Mississippi River Delta sediments at a rate of 200 to 1,000 $\mu g/cm^2$/year. This diffusion depletes the delta sediments in manganese by about 50% and should affect bottom-water manganese concentrations, but bottom water was not analyzed. Iron is also reduced and mobilized in sediments, and high iron values are found in nearshore sediment pore water. However, iron flux out of sediments is less than that of manganese, and fluxes of cadmium, nickel, lead, etc., are probably even less, but this has not been well documented. It is possible that reductive mobilization is especially significant in the carbonate-rich and organic-rich sediments of South Florida because a significant percentage of some trace metals may be associated with organic matter. As organic matter decays, the metals would be released in an environment with little clay to adsorb them. More work is needed on this subject, because benthic organisms would be exposed to sediment pore water and might be affected by high trace metal concentrations or high levels of such chemicals as ammonia and sulfide, which also build up in pore water.

Suspended in Water

Non-Living Particulate Matter. Most particulate matter transported to the sea by rivers settles out very near the river mouth, including even the very fine-grained clay material. Thus, a river plume, such as that of the Mississippi River, is highly visible, with a sharp transition from muddy to clear water. Several factors contribute to this rapid settling of river particulates, including lower current speeds and higher salinity in the ocean, which tends to flocculate clay particles. Zooplankton can also aid in sinking of clay particles by packaging them into fecal pellets which sink rapidly.

Total suspended matter (TSM) in rivers varies considerably from river to river and season to season as a function of river flow, but is commonly 10 to 100 mg/L. In contrast to river TSM values, coastal seawater values are low and can vary due to variations in both inorganic and biological particles. Nelsen and Trefry (1986) found 6 to 7 mg/L TSM at a station very near the Mississippi River mouth when concentrations in the river were 180 mg/L. A few kilometers away at mid shelf, TSM dropped to 2 to 3 mg/L, and at the shelf break, to 0.3 to 0.5 mg/L. Open Gulf of Mexico TSM values are typically 10 to 100 μg/L--that is, 5 to 50 times lower than the shelf break values.

Manker (1975) found 2 to 4 mg/L TSM in Florida Bay and adjacent areas in 1973, and 0.5 to 1.5 mg/L in 1974. He reported the latter values are more typical, due to

improvements in his sampling techniques, but he also cautioned that concentrations vary widely in these shallow waters with wind speed variations. Mathis (1973) found ~15 mg/L TSM at the mouths of the Shark and Broad Rivers, values two to three times higher than those measured in the headwaters of these rivers. It would be very unusual to find higher TSM values in the coastal marine environment than in rivers in most parts of the world, but the South Florida rivers are low in TSM. Most TSM in South Florida coastal marine environments is resuspended bottom sediment or plankton, not river-derived material.

Most TSM values are obtained by filtering a discrete water sample of 100 to 1,000 mL. A problem with this procedure is that it can miss large particles, which sink rapidly and which may carry most of the mass that is sinking toward the seafloor; thus, measured TSM values might not be a good indicator of flux to the bottom. A second problem arises when the chemistry of the particulate matter is to be determined. If, as is usually the case, this is done by analyzing material caught on filters, the material may not be typical of what is sinking, and the filter is likely to hold so little material that great skill is needed for proper analysis. For these reasons, there is relatively little information on the chemistry of suspended matter in South Florida bays and estuaries, and some of the available data are of questionable quality.

Manker (1975) reported chromium, cobalt, and mercury data on suspended matter samples collected at 37 locations from southern Biscayne Bay, south through Card and Barnes Sounds, Florida Bay, and along the Florida Keys to near Alligator Reef (**Table 3.1**). Thus, the Upper Keys were well sampled, but no samples were taken in the Big Pine Key/Key West area. The samples were collected on glass fiber filters, which is not a good technique, and were analyzed by neutron activation, which is not a reliable technique for mercury. The mercury data are thus almost certainly in error, as the values are orders of magnitude higher than values for the likely source material (bottom sediments and plankton). The cobalt and chromium values in suspended material are much higher than those of bottom sediments (to be discussed below), but the increases in these cases could be due to the finer grain size of the suspended material.

Table 3.1. Trace metal concentrations in sediment, suspended particulates, and corals from the Florida Keys and carbonate sediment and phytoplankton from the Gulf of Mexico.

Type of Sample	Metal Concentration (μg/g dry wt)				
	Co	Cr	Hg	Pb	Zn
Bottom sediments (bulk)*	0.2	9	0.4*	26*	4
Bottom sediments (<4 μm)*	25	19	17*	–	25
Suspended particulates*	7	137	28*	–	–
Corals*	0.2	0.8	0.1*	–	2
Gulf carbonate sediment†	–	13	0.1	2	6
Gulf phytoplankton§	3	–	0.3	20	50

* Manker (1975). Hg and Pb values are considered unreliable (see text).
† Trefry et al. (1978), except Hg from Presley unpubl. data.
§ Trefry and Presley (1976), except Hg from Windom et al. (1973) for Atlantic phytoplankton.

Mathis (1973) analyzed suspended matter caught on Millipore filters in 23 to 25 ppt salinity waters at the mouths of the Broad and Shark Rivers for cadmium, copper, iron, and manganese. The cadmium values obtained are about 10 times higher than values for bottom sediment in this area as determined during the National Oceanic and Atmospheric Administration (NOAA) Status and Trends program (**Table 3.2**), but the copper, iron, and manganese values are very similar to the Status and Trends values. It seems likely that the Mathis (1973) cadmium values are too high, but a grain size or composition effect cannot be ruled out.

Plankton. In addition to the problems discussed above regarding the sampling and analysis of non-living suspended matter, sampling and analysis of plankton present further problems. Plankton must be sampled with a net, usually attached to a metal wire and pulled by a ship. Metal particles from the wire can be incorporated into the sample, as can paint chips and other debris from the hull of the ship. Furthermore, inorganic matter suspended in the water is mixed with the plankton by the net. Essentially no reliable data are available on trace element levels in plankton from the study area. Gilio and Segar (1976) collected plankton, but admitted to analytical problems in analysis and used only their own copper and zinc values while estimating other metals from world average data (see Table 3.7 later in this chapter).

Sediments

Marine sediments are usually considered to be the ultimate sink for trace metals added to the ocean, and that is certainly true after the trace metals have been buried a meter or so deep in the sediment column. However, trace metals can be returned to the water column from a few centimeters deep in the sediment column by mobilization processes that solubilize them. Either molecular diffusion or physical disturbance within the sediment can transfer soluble metals to the water column. In spite of the processes that can return trace metals to the water column or make them available to organisms living in the sediment, the sediment column represents, in general, a record of past and present trace metal inputs to the marine environment. As such, sediment data provide valuable information to environmental monitoring studies. An example of using sediment analyses for a historical perspective on pollutant inputs to Gulf of Mexico sediments is given by Presley et al. (1980).

Skinner and Jaap (1986) reported trace element data for sediment collected in the John Pennekamp Coral Reef State Park and the Key Largo National Marine Sanctuary. Samples were collected at 20 stations in 1985, and at 14 and 8 of the 20 stations on subsequent sampling trips in 1986. Samples were analyzed for arsenic, cadmium, copper, mercury, and lead by Dr. Eugene Corcoran at the University of Miami, using "Standard Methods for the Examination of Water and Wastewater" (American Public Health Association 1976). This method uses hot nitric acid to leach the sample, so it should recover most (>80 to 90%) of the metal content of these carbonate-rich sediments.

Most stations sampled by Skinner and Jaap (1986) were within 10 to 1,000 m of island shorelines in about 1 m water depth. Three stations were 7 to 10 km (3.8 to 5.4 nmi) offshore around coral reefs in water depths of 15 to 25 m, and four stations were in intermediate locations. All sediment was carbonate-rich, but came from a variety of sources and had particle sizes varying from mud to gravel. No table of the data was given in the manuscript, but arsenic values were reported to range from <0.1 to 9.9 μg/g, with more than 50% of the samples having <0.1 μg/g and the high values occurring near human developments.

Table 3.2. Concentrations of major and trace elements in South Florida coastal sediments and suspended matter.

Site	Metal Concentration*												
	Ag	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Si	Sn	Zn
SEDIMENTS†													
Naples Bay													
Mean	0.06	5.0	0.14	34.	10.7	0.54	0.04	48.	5.	4.6	25.	0.5	27.
SD	0.03	1.5	0.06	15.	4.7	0.24	0.01	19.	2.	2.5	6.	0.3	11.
Rookery Bay													
Mean	0.03	5.1	0.15	58.	4.2	0.64	0.05	75.	9.	4.1	13.	0.6	18.
SD	0.01	1.9	0.04	5.	0.8	0.05	0.02	40.	1.	3.2	5.	0.3	2.
Faka Union Bay													
Mean	0.02	3.1	0.12	49.	2.6	0.70	0.04	73.	8.	4.4	24.	0.3	12.
SD	0.02	2.1	0.07	32.	1.6	0.52	0.02	49.	5.	3.6	12.	0.2	8.
All three above													
Mean	0.04	4.4	0.14	47.	5.8	0.63	0.04	65.	7.	4.4	21.	0.5	19.
SD	0.03	2.0	0.06	22.	4.5	0.32	0.02	38.	4.	3.0	9.	0.3	10.
Gulf of Mexico													
Mean	0.12	6.5	0.20	47.	11.7	1.96	0.07	394.	16.	20.2	30.	1.34	57.
SD	0.24	4.5	0.24	23.	7.9	1.12	0.09	365.	9.	19.9	9.	0.9	30.
SUSPENDED MATTER§													
Broad River Estuary													
Mean			1.0§		4.9	0.53		280					
SD			0.2		1.5	0.15		230					
Shark River Estuary													
Mean			1.7§		12.	0.69		260					
SD			0.9		4.	0.17		170					

* Values in $\mu g/g$ dry wt, except Fe and Si in percent dry wt.

† Brooks et al. (1988), National Oceanic and Atmospheric Administration Status and Trends Program. Averages of three stations at each site sampled in 1986 and 1987. Naples Bay--sediment mostly from boat channels. Rookery Bay (Henderson Creek)--sediment from among mangrove roots. Faka Union Bay (Everglades)--sediment from among mangrove roots. Gulf of Mexico--average of values from 150 stations along entire U.S. Gulf coast (Texas to Florida).

§ Mathis (1973). Cd values questionable (see text).

Skinner and Jaap (1986) reported that cadmium concentrations ranged from <0.05 to 0.32 μg/g, with most stations being below 0.1 μg/g. Copper concentrations ranged from <1 to 20 μg/g, and high values tended to be from samples near boat docks or other developments. Mercury concentrations ranged from <0.05 to 0.2 μg/g and were low at most stations. Only Garden Cove and Largo Sound were at the 0.2 μg/g level for mercury. Lead concentrations were <0.2 μg/g at several stations and 8 μg/g at the Harrison development site in July 1985. Skinner and Jaap (1986) reported that nearshore stations were generally higher in lead than offshore stations, as was true for other toxic metals, but the actual data were not given, so the magnitude of the difference cannot be assessed. It should also be pointed out that the nearshore sediments are likely to be of a different grain size, have a different organic carbon content, and consist of different skeletal carbonate than the offshore sediments. The two are thus difficult to compare, and higher concentrations of trace metals nearshore might have nothing to do with human activities.

Heatwole (1987) monitored water quality parameters (dissolved oxygen, coliform bacteria, nutrients, etc.) and copper, iron, lead, mercury, and zinc in sediments from sites near Marathon, Florida. This is one of the most developed areas in the Keys, with about 25% of the total artificial waterways, sewage treatment plants, marinas, and seafood processors in Monroe County. The one-year monitoring study was designed to assess pollutant inputs from each of these potential sources.

Sampling stations were occupied near each of the five potential pollutant sources and at a station about 1,000 m away. In addition, a station was located farther offshore in Florida Bay as well as offshore in the Atlantic Ocean. Trace metal concentrations were low and similar at all control stations, and have been combined in **Table 3.3**; however, the concentrations were high and variable at stations near pollutant sources. The lead data given are almost certainly in error and should be ignored, as the control site values are 10 times higher than values from other investigators; the mercury data are useless because of the high detection limit.

Table 3.3. Trace metal concentrations in sediment from the Marathon area in the Florida Keys (From: Heatwole 1987).

Station*	Metal Concentration (μg/g dry wt)				
	Cu	Fe	Hg†	Pb†	Zn
Faro Blanco	72	1,300	1.0	58	56
Fish Market	81	2,300	<0.02	79	78
Shopping Center	38	5,100	0.02	52	48
Beach	10	1,200	<0.02	42	10
Canal	100	2,600	0.02	78	115
Control	5	400	<0.02	45	10

* Station locations: Faro Blanco–marina with live-aboard boats. Fish Market–seafood processor, boat harbor. Shopping Center–parking lot drainage. Beach–Key Colony Beach sewage treatment plant. Canal–90th Street Canal, septic tank leachate. Control–bayside and oceanside control stations.

† Pb data are considered unreliable; Hg data are useless because of high detection limit (see text).

Some copper and zinc enrichments in **Table 3.3** can be attributed to a grain size and/or mineralogy effect, as can be judged from the variation in iron content. Contrary to Heatwole's (1987) conclusion, it is unlikely that humans have affected the iron content of the sediment. A better picture of trace metal enrichments would be gained by looking at ratios of each metal to iron. Even on a ratio-to-iron basis, however, enrichments in copper and zinc are evident at the Faro Blanco Marina, Fish Market, and 90th Street Canal sites. The shopping center drainage area sediment has high iron but low copper and zinc, and the Colony Beach sewage treatment plant area is low in all metals. Some activity associated with boats (e.g., copper-based antifouling paints and zinc sacrificial anodes) seems the most likely source for the copper and zinc enrichments.

Presley and Boothe (unpubl. data) analyzed samples from four sites on the Southwest Florida shelf north of the study area for barium, chromium, and iron. Three replicates from each site were analyzed by neutron activation. Samples varied considerably in grain size and therefore in metal content, but were low in metals compared with silt-rich or clay-rich Gulf of Mexico sediments. Barium ranged from 22 to 60 μg/g, chromium from 11 to 16 μg/g, and iron from 0.16 to 0.33%. Additions of metals by humans would be readily apparent in these sediments.

Manker (1975) not only determined trace metals in suspended particulate matter but also analyzed bottom sediment from about 30 locations along the upper half of the Florida Keys (**Table 3.1**). Both shallow water bays and lagoons and offshore reef areas such as Carysfort and Molasses Reefs were sampled. Samples were analyzed for chromium, cobalt, mercury, and zinc by neutron activation, and for lead by atomic absorption. The separated <4-μm size fraction was analyzed, as well as the bulk sample, and much higher concentrations of all metals were found in the fine fraction. This observation is consistent with observations elsewhere, which show fine-grained sediment to be enriched in trace metals.

Manker's (1975) bulk sediment values for mercury and especially for lead seem to be too high based on other values from South Florida. For example, Manker's lead value is more than five times higher than the average value for South Florida sediment collected during the NOAA Status and Trends Program (**Table 3.2**); more than 10 times higher than the value reported in **Table 3.4** by Trefry et al. (1978) for Mississippi-Alabama-Florida (MAFLA) carbonates; and about 10 times higher than values for South Florida coastal sediment reported by the Florida Department of Environmental Regulation (**Table 3.5**). Manker's mercury value also seems to be too high by a factor of 10 based on other analyses (**Table 3.1**). It is likely, however, that fine bottom sediment and suspended sediment in this area have higher trace metal concentrations than coarser material. Better documentation is needed on the magnitude of such enrichments.

Manker (1975) claimed that sampling sites near population centers, highways, boat basins, power plants, etc. produced sediments enriched in trace metals compared with sediments from more isolated locations. Especially high trace metal concentrations were found near a storm sewer outfall on Tavernier Key, a marina on Key Largo, a lagoon in Florida Bay, and a power plant at Turkey Point (Biscayne Bay). The extremely large differences in concentration between bulk and <4-μm fraction samples make these data difficult to interpret. Some of these differences could easily be due to grain size differences and have nothing to do with human activities. However, trace metal enrichments around the Turkey Point power plant have been reported by others, as is discussed below.

Table 3.4. Average trace metal concentrations in South Florida carbonate and quartz sand sediments, average limestone and sandstone, and average upper continental crust.

	Metal Concentration*						
	Cd	Cr	Cu	Fe	Ni	Pb	Zn
Carbonates†	0.15	13	1.3	0.19	3.4	2	6
Quartz sand§	0.03	4	0.03	0.06	0.7	1	2
Limestones¶	0.03	11	5.5	1.7	7	5.7	20
Sandstones¶	0.05	35	30	2.9	9	10	30
Average Crust**	0.1	35	25	3.5	20	20	71

* All concentrations in µg/g dry wt, except Fe in percent dry wt.
† Trefry et al. (1978). Samples with >90% $CaCO_3$.
§ Trefry et al. (1978). Samples with <10% $CaCO_3$ and <10% fines.
¶ Bowen (1979).
** Taylor and McClennan (1985).

Table 3.5. Trace metal concentrations in coastal and offshore (carbonate) sediments from South Florida.

	Metal Concentration*									
	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn
E. Florida Bay†										
Mean	3.5	0.03	–	2.3	0.21	0.01	102	3.6	2.7	4.8
SD	0.6	0.005	–	1.4	0.02	0.01	180	0.7	0.3	0.8
W. Florida Bay and SW Florida Coast§										
Mean	2.4	0.05	13	2.5	0.32	0.02	158	4.1	2.9	5.6
SD	0.5	0.009	2	0.3	0.04	0.00	21	0.7	0.6	1.1
Offshore SW Florida¶										
Mean	–	0.08	7.5	0.9	0.15	–	–	3.5	3.2	6.0
SD	–	0.02	2.0	0.1	0.05	–	–	0.5	0.3	2.0

* Values in µg/g dry wt, except Fe in percent dry wt.
† K. Swanson, pers. comm. (1989), Florida Department of Environmental Regulation. Six stations in eastern Florida Bay, one in Barnes Sound.
§ K. Swanson, pers. comm. (1989). Six stations in western Florida Bay, 11 in Whitewater, Gullivan, and Rookery Bays.
¶ Woodward-Clyde Consultants and Continental Shelf Associates, Inc. (1983). Eight samples of >94% $CaCO_3$ from the Southwest Florida Shelf Ecosystems Study.

Segar and Pellenbarg (1973) reported on analyses of sediment samples collected near the Turkey Point power plant and from Card Sound, which is just south of the power plant. Average values for several trace metals at these two locations are similar to those found by Brooks et al. (1988) in three estuaries in the Everglades City area (**Tables 3.2** and **3.6**). However, Segar and Pellenbarg (1973) found higher concentrations of metals near the mouth of the cooling water effluent canal for the Turkey Point power plant. Enrichments were especially evident for copper, nickel, and vanadium. Segar and Pellenbarg (1973) suggested that these enrichments are due to either construction or operation of the plant, which was about four years old in 1973. The canal mouth data are given only as contours on a map for copper, nickel, and vanadium; thus, it is not possible to look for a corresponding enrichment in iron, which might suggest a grain size effect as contributing to the enrichments. However, the copper, nickel, and vanadium concentrations are high, even for very fine sediment. More recent data are needed to supplement the 1973 data and to assess the longer term influence of the power plant. It may well be that the shallow Florida bays with restricted circulation are especially susceptible to contamination from power plant and industrial effluents.

Two of the NOAA Status and Trends sites are within the study area, and one is just outside of it. Three samples were taken at each of these three sites in 1986 and again in 1987. The data have been averaged and are shown in **Table 3.2** along with overall averages for all Status and Trends sites in the Gulf of Mexico. The South Florida sites have about one-third the iron of average Gulf of Mexico sites and about one-half to one-third of the copper, lead, nickel, silver, tin, and zinc. They are, however, only slightly lower in arsenic and cadmium, lower in mercury by less than a factor of two, and equal to average sediment in chromium. South Florida sediment is thus different from average Gulf of Mexico sediment. Furthermore, Florida coastal quartz sands are lower in trace metals than are carbonates, as is seen in **Table 3.4**. It seems likely, however, that the carbonates vary depending on the shells and tests making them up, or on environmental factors. For example, the offshore carbonate data (**Table 3.5**) show lower trace metal concentrations than nearshore values.

Table 3.6. Trace metal concentrations in sediment from Card Sound and southern Biscayne Bay (Turkey Point area), including the mouth of a power plant effluent canal, compared with concentrations in three other South Florida estuaries sampled during the National Oceanic and Atmospheric Administration Status and Trends program.

	Metal Concentration*							
	Ag	Cd	Cu	Fe	Ni	Pb	V	Zn
Card Sound†	0.5	0.7	2	0.19	<2	1	24	4
Turkey Point§	0.4	0.2	11	0.26	25	3	52	12
Effluent canal¶	–	–	40	–	150	–	200	–
NOAA Status and Trends**	0.04	0.14	6	0.6	7	4	–	19

* Values in µg/g dry wt, except Fe in percent dry wt.
† Segar and Pellenbarg (1973). Mean of 82 samples.
§ Segar and Pellenbarg (1973). Mean of 33 samples.
¶ Segar and Pellenbarg (1973). Mean value at mouth of Turkey Point power plant effluent canal.
** Brooks et al. (1988). Mean of 18 samples from three South Florida estuaries.

Currently, Drs. Robert Braman, Dean Martin, and Richard Strom from the Chemistry Department at the University of South Florida, Tampa are analyzing samples they collected along six transects (18 stations) off the Florida Keys from Key Biscayne to the Dry Tortugas. The samples consist of 54 samples each of bottom sediments, primary producer organisms (green alga *Halimeda* or seagrass *Thalassia*) and consumer organisms (mostly sponges: *Haliclona rubens*, *Spheciospongia vesparium*, and *Xestospongia muta*). The samples are being analyzed for arsenic (inorganic and methyl), cadmium, copper, lead, mercury, and tin, as well as pesticides. No data from this project were available when the present report was written.

Benthic Organisms

The tropical South Florida study area is home to an abundant and diverse assemblage of marine organisms, with extensive mangrove forests, seagrass beds, and benthic algal colonies forming the base of a food chain that culminates in many commercially and recreationally important finfish and shellfish stocks. Ideally, a reliable data set would be available that would list background values for all potentially toxic metals in each ecosystem component. This ideal situation does not exist, but a number of studies of trace metals in organisms in the area have been conducted.

Gilio and Segar (1976) presented data and a model for movement of cadmium, copper, iron, lead, vanadium, and zinc through the Card Sound ecosystem. Data were collected in 1971 and 1972 and seem to be of high quality. The research was aimed at obtaining an inventory of metals in various ecosystem compartments and fluxes of metals between compartments. For example, total masses of water and sediments in Card Sound were estimated, as was the total biomass for various organisms (turtle grass, algae, sponges, etc.). Total mass was multiplied by average concentration of each metal to arrive at a total inventory. Estimates were then made of turnover times (e.g., annual productivity of each organism, flushing time of water through the Sound) and transfers between compartments.

Gilio and Segar (1976) reported that the highest amounts of all elements were found in sediments, followed by water, and then by living organisms. Living organisms and water, however, turn over trace metals much more rapidly than does sediment and would thus respond more quickly to anthropogenic additions. **Table 3.7** presents data obtained by Gilio and Segar (1976) on trace element concentrations in those organisms (mostly plants) important to the overall biomass or element cycling in Card Sound. The data show a somewhat surprising uniformity in concentration of a given metal in the various organisms, with factor-of-two differences much more common than factor-of-10 differences. Some major differences were found; for example, the calcareous algae *Laurencia poitei* averaged 96 μg/g in vanadium, whereas red mangrove (*Rhizophora mangle*) leaves had only 0.43 μg/g. However, these differences were the exception.

In the study by Gilio and Segar (1976), turtle grass (*Thalassia testudinum*) had the largest inventory of all trace metals due to its large biomass, followed closely by sponges; large rooted algae were approximately 10 times lower. Phytoplankton and other organisms constituted a minor part of the total trace metal inventory. Presumably, phytoplankton would prove to be minor contributors to the primary productivity of shallow-water bays in South Florida. Thus, trace metal analyses should concentrate on seagrass and benthic algae. Turtle grass in Card Sound, after death and decay, accounted for most movement of cadmium, iron, and lead from sediments to water. It was suggested, but not proven, that living turtle grass "pumps" trace metals from sediments to water and thus might be even more important than it appears to trace metal cycling. Phytoplankton and epiphytes seem to account for about one-third the primary productivity of turtle grass, and thus might cycle most of the copper, vanadium, and zinc through the Card Sound system.

Table 3.7. Trace element concentrations for marine organisms of Card Sound, Florida (From: Gilio and Segar 1976).

	Metal Concentration (μg/g dry weight) Mean ± Standard Error					
	Cd	Cu	Fe	Pb	V	Zn
MACROFLORA						
Thalassia testudinum (46)*	0.2±0.021	1.6±0.33†	320±46	0.72±0.16	8.5+1.2	18±1.3
Laurencia poitei (14)	0.2±0.047	12 ±2.4	420±75	0.59±0.16	96.0±58	34±5.1
Penicillus capitatus (34)	0.11±0.012	1.2±0.17	560±77	1.1 ±0.21	4.8±0.72	12±3.5
Halimeda incrassata (4)	0.16±0.12	0.7±0.26	230±75	1.2 ±0.56	2.4±0.78	3.7±1.2
Rhizophora mangle (7)						
Live leaves	0.044±0.028	1.3±0.67	100±76	0.39±0.11	0.43±0.29	3.1±0.88
Dead leaves	0.240±0.110	5.8±4.6	71±20	0.79±0.23	0.52±0.22	2.3±0.52
Seedlings in water (3)	0.017±0.0059	0.81±0.79	12±5.6	0.23±0.17	0.48±0.41	2.2±0.58
Decaying stems in water(2)	0.056±0.055	0.52±0.46	140±0	0.099±0.007	0.056±0.055	8.1±5.9
MICROFLORA						
Phytoplankton§	0.20	12±8.0	730	0.33	0.33	180±80
Epiphytes on *Thalassia* blades¶	0.20	21±9.4	420	0.59	96	150±59
MACROFAUNA						
Detritivores and Carnivores (4)	0.19±0.08	7.4±0.67	41±8.9	0.39±0.15	0.77±0.07	28±20
Sponges (7)	0.44±0.18	3.7±1.5	530±150	0.36±0.15	2.8±1.5	24±9.8

* Numbers in parentheses are the number of samples analyzed.
† Possible error due to a high Cu blank.
§ Values for Cd, Fe, Pb, and V given as 15-fold lower than Bowen's 1979 data based on Cu and Zn values determined in this study being 15-fold lower than Bowen's values.
¶ Values for Cd, Fe, Pb, and V assumed to be the same as those for *Laurencia poitei*.

Skinner and Jaap (1986) (**Table 3.8**) reported on the analysis of a variety of invertebrate organisms collected in the John Pennekamp Coral Reef State Park and the Key Largo National Marine Sanctuary. Samples were collected at 20 locations in 1985, and at 14 and 8 stations during two sampling trips in 1986. At each station, two to four species, judged to be the dominant species at the location, were collected by divers. Some stations were in shallow water (~1 m) nearshore, and some were in deeper water (~25 m), 5 to 10 km (2.7 to 5.4 nmi) offshore. Most samples were turtle grass (*Thalassia testudinum*), green algae (*Halimeda* sp.), coral (*Montastraea annularis*, *Porites porites*, and others), or sponges. The samples were analyzed by Dr. Eugene Corcoran at the University of Miami.

The report by Skinner and Jaap (1986) does not list all data but rather simply gives the highest and lowest values obtained for each metal on each sampling trip for each station and the organism in which these ranges were found. The data presentation and extreme variability in metal concentrations for a given species make data interpretation almost impossible. The report claims to show higher concentrations at nearshore stations near areas disturbed by humans, but this is difficult to see in the data as presented. An additional problem is that many samples were below the detection limit for cadmium (<0.3 to <3.0 μg/g), lead (<1 to <10 μg/g), and mercury (<0.1 μg/g). The coral data are especially difficult to evaluate, as no indication is given as to the relative amounts of hard and soft tissue in a given sample. Some seagrass and algal samples probably had considerable inorganic matter associated with them, based on the aluminum and iron data.

Manker (1975) analyzed eight coral samples as part of his study of sediments. These data are given in **Table 3.1**, where it can be seen that the concentrations for the elements determined are very low, making it difficult to believe his contention that trace metals might be affecting the corals.

Mathis (1973) analyzed red mangrove (*Rhizophora mangle*) leaves and their decomposition detritus for cadmium, copper, iron, and manganese to assess their contribution to heavy metals in South Florida estuaries. In comparing the Barron River estuary, which receives its drainage from agricultural areas, with the Shark and Broad River estuaries, which receive drainage from undeveloped areas, Mathis found a significant enrichment of cadmium and copper in Barron River mangrove leaves and an enrichment of copper, iron, and manganese in Barron River detritus. These differences were attributed to human activities. Mangrove leaf detritus, taken from the rivers and estuaries, was also greatly enriched in trace metals compared with living or dead leaves. This was attributed to sorption of dissolved metals by organic detritus, but could also be due to contamination of organic detritus with inorganic matter.

Oysters. Oysters provide a number of advantages as organisms to analyze in pollution monitoring studies. They are sessile and relatively easy to collect, can often be found in large stable populations that allow repeated sampling, are good concentrators of several trace metals, are easy to analyze, respond to changes in metal concentration in the environment, and are commercially important. The Gulf of Mexico component of the NOAA Status and Trends (Mussel Watch) Program therefore uses oysters exclusively. Two Mussel Watch sites are within the South Florida study area (Rookery and Faka Union Bays), one is just barely outside the area (Naples Bay), and one is about 50 km (27 nmi) north of the area (Charlotte Harbor). At each site, 20 oysters were collected at each of three stations during the winters of 1986, 1987, 1988, and 1989 (Brooks et al., 1988). Oysters from each station were homogenized to make a single sample each year.

Table 3.9 shows data from the first three years of the NOAA Status and Trends Program. Each value is the average of the three stations and the three years (nine samples of 20 oysters each). In general, there is more variation in trace metal concentration between sites than between stations at a site or between years. Thus, the data characterize a given site, and the sites differ.

Table 3.8. Trace metal concentrations in nearshore and offshore organisms in the Florida Keys (From: Skinner and Jaap 1986).

Sample	Metal Concentration*					
	As		Cu		Fe	
	nearshore	offshore	nearshore	offshore	nearshore	offshore
Turtle grass†	0.5-19.3	<0.5-7.2	3-13	2- ?	? -385	? -480
Green algae§	? -3.9	? - ?	3-21	? -110	6- ?	? - ?
Corals¶	0.2- ?	<0.5-4.8	? - ?	? -9.5	10- ?	10- ?
Sponges**	? - ?	? - ?	1-23	? - ?	10-4800	? - ?

* All values in µg/g dry wt (Cd, Hg, and Pb below determination limit in almost all specimens).
† *Thalassia testudinum*.
§ *Halimeda* spp.
¶ *Acropora cervicornis*, *Acropora palmata*, *Diploria clivosa*, *Montastraea annularis*, and *Porites porites*.
** *Haliclona* sp.and *Spheciospongia vesparium*.
? indicates no data given.

Table 3.9. Trace metal concentrations in oysters from the National Oceanic and Atmospheric Administration Status and Trends Program (From: Brooks et al. 1988).

Site	Metal Concentration*												
	Ag	As	Cd	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Se	Sn	Zn
NAPLES BAY													
Mean	4.09	25.6	1.59	0.76	326	296	116	9.18	0.81	0.23	1.73	0.69	2700
SD	0.80	3.85	0.55	0.29	41.9	116	40.1	1.82	0.18	0.10	0.48	0.35	558
ROOKERY BAY, HENDERSON CREEK													
Mean	2.10	28.3	1.96	1.65	123	396	234	8.62	1.16	0.33	2.15	0.14	1150
SD	0.52	2.40	0.49	0.65	48.3	150	67.2	2.80	0.26	0.27	0.45	0.08	399
FAKA UNION BAY, EVERGLADES													
Mean	0.96	7.98	2.41	0.74	44.5	233	197	8.43	1.12	0.20	2.07	0.12	987
SD	0.35	0.92	1.11	0.64	8.70	97.4	50.0	2.37	0.49	0.14	0.45	0.03	340
GULF OF MEXICO†													
Mean	2.17	10.3	4.09	0.59	146	294	128	14.4	1.77	0.69	3.07	0.21	2160
SD	1.44	7.56	2.41	0.68	96.7	161	107	7.50	1.58	1.04	1.47	0.20	1580

* Values in µg/g dry wt, except Hg in µg/kg dry wt.
† Three-year average of values from 150 stations along entire Gulf coast.

Some contrasts among sites in South Florida and between South Florida sites and averages from all Gulf of Mexico sites can be noted in the data. For example, arsenic concentrations in oysters from Naples and Rookery Bays (and from Charlotte Harbor, which is outside the area and is not shown) were the highest on the Gulf coast, being about three times the average value. Faka Union Bay oysters, in contrast, were slightly below average in arsenic content. This persistent trend must have an environmental cause, but that cause has not yet been determined.

Naples Bay oysters are enriched in copper and silver by about a factor of two compared with the Gulf of Mexico average, but they are average in other metals (chromium, iron, mercury) and below average in others (cadmium, lead, nickel, and selenium). Rookery and Faka Union Bay oysters are enriched in mercury by a factor of two and depleted in zinc by a factor of two. All three South Florida site oysters are about a factor of two lower in lead than the average Gulf of Mexico value and are lower than two sites in Tampa Bay by a factor of five or more. It seems likely that the availability of metals in the different sites controls the concentrations in oysters, but it is not possible to determine from the existing data whether the variability in availability is natural or human-induced.

Conclusions

There are few reliable data on trace metals in water, sediments, and organisms of the South Florida study area. In fact, there are probably no reliable data on concentrations of trace metals dissolved in the waters of the shallow bays and lagoons of the area. A few data thought to be reliable for offshore waters in the area show concentrations of dissolved trace metals similar to those that have been found in other continental shelf areas. It is possible that dissolved trace metal concentrations are higher in South Florida bays and estuaries than elsewhere because of the scarcity of alumino-silicate material which effectively adsorbs these metals.

Trace metal concentrations in sediments from the study area are very low compared with those reported for most other coastal areas. The low values found for most trace metals are largely a consequence of the South Florida sediments being almost pure biogenic carbonate, which is naturally low in trace metals. It is also true that a relatively small land area drains into the study area and much of it is not highly industrialized. There are suggestions of higher trace metal concentrations in sediments near a large power plant and near boat marinas. Some reported data may be unreliable because of difficulties in analyzing carbonate-rich, trace-metal-poor sediment. Low trace metal concentrations in the sediment and the small amount of recent sediment cover make contamination of the sediment by humans a distinct possibility. This is in sharp contrast to the northern Gulf of Mexico, where huge volumes of clay-rich, trace-metal-rich Recent sediment effectively dilute additions of most metals by humans.

Organic primary productivity in shallow waters of the study area is dominated by seagrass and benthic algae, rather than phytoplankton as is the case in most marine areas. According to reported data, these plants have trace metal concentrations comparable to or even higher than associated sediments. No data are available on uptake of pollutant metals by these plants, but they provide a potential pathway for entry of trace metals into the marine food web. Sponges and corals are abundant in the study area. Trace metal concentrations in these organisms are highly variable but comparable to sediment and seagrass. Oysters at some sites in the area are enriched in some trace metals (e.g., arsenic and silver) but depleted in others (e.g., cadmium and lead) compared with average Gulf of Mexico oysters. No data could be found on trace metals in fish or shrimp from the area.

Based on the data available on trace metal distributions in the South Florida study area, it is obvious that additional work is needed on water, sediment, and organisms.

Trace metal data from water are almost non-existent and are of doubtful reliability. To obtain high quality data and to be sure they are representative of the area would, however, require a major sampling and analytical effort. Power plant and other industrial effluents would be easier to analyze and would indicate the potential for dissolved metal additions by humans. Sediment and organisms, however, have much higher concentrations of trace metals than water and are therefore less prone to contamination during sampling and processing. They are also easier to analyze reliably, and they integrate metal concentrations over weeks to years, thereby giving a better average picture of an area.

The first priority for additional study of trace metals in South Florida is to obtain more and better data on concentrations in sediments and organisms. A second priority is the analysis of seawater from coastal bays (not the open ocean) and from the vicinity of wastewater outfalls.

In collecting new sediment trace metal data, methods must be well documented and standard reference materials must be analyzed so that the reliability of the data can be judged. Better documentation is needed of the apparent trace metal enrichments in sediments near boat marinas, power plant outfalls, etc., especially for highly toxic metals such as arsenic, cadmium, lead, mercury, and selenium. To aid in data interpretation, iron and/or aluminum should be analyzed with these other metals in sediments, and grain size should be determined.

More and better data are needed on trace metal concentrations in organisms from the study area, but emphasis should be placed on analyzing only a few species and collecting these at many representative sites, both near and well away from suspected pollution sources. Bivalves are among the easiest organisms to collect and analyze and are good indicators of pollution even if they are not a dominant organism in the area. Seagrass is also easy to work with and is abundant in the area. Sponges, corals, and the like are difficult to analyze and best avoided. Fish species that spend most of their life in a geographically restricted area (e.g., a coastal bay) should be analyzed if available.

HYDROCARBONS

Edward S. Van Vleet

Hydrocarbon Sources

Potential sources of hydrocarbons to the marine environment can be divided into two broad groups: natural sources and anthropogenic sources. Specific source inputs included in these groups are summarized in **Table 3.10**. Of the natural sources of hydrocarbons to the oceans, biogenic marine and terrigenous inputs normally dominate in clean areas, whereas natural petroleum seeps, while not widespread, can be the major contributor on a more local scale. Considering only anthropogenic sources, coastal environments and estuaries are normally dominated by hydrocarbons originating from municipal and industrial wastes and runoff. In the open sea, however, anthropogenic hydrocarbons are often dominated by inputs from oil transportation activities. In some cases, incomplete fossil fuel combustion products transported from land and deposited over the ocean may be a major contributor. In other localized areas, ocean dumping of waste products enriched in petroleum may dominate hydrocarbon inputs. Although all of the sources listed in **Table 3.10** may not be contributing significant amounts of hydrocarbons to the study area at the present time, each of these processes is clearly occurring within the Gulf of Mexico and may therefore play a role in the long-term accumulation of hydrocarbons in the study area. It is therefore important to briefly summarize what is known about each input source so that conclusions can then be drawn about which processes are currently dominating hydrocarbon input to the study area.

Table 3.10. Potential sources of hydrocarbons to the marine environment.

NATURAL SOURCES
Biogenic Marine
Biogenic Terrigenous
Natural Seeps
ANTHROPOGENIC SOURCES
Land Sources
Municipal Wastes
Industrial Wastes
Automobiles
Runoff
At-Sea Sources
Shipping Activities
Oil Production Operations
Oil Well Blowouts
Ocean Dumping and Incineration

Several hydrocarbons are synthesized naturally by most marine and terrestrial plants and animals. Other organisms accumulate hydrocarbons from their diet. Several chemical characteristics allow differentiation of biogenic inputs from petroleum inputs. Most living organisms produce only a limited number of hydrocarbons that have a very narrow boiling (molecular weight) range. Marine biogenic inputs are often characterized by the presence of odd-carbon-numbered n-alkanes nC_{15}, nC_{17}, and nC_{19}. Terrestrial biogenic inputs are characterized by odd-carbon n-alkanes in the nC_{23} to nC_{33} range. Biogenic inputs are also noted by the predominance of a single isoprenoid hydrocarbon, pristane. Phytane, a similar isoprenoid compound, is rarely found in natural biogenic sources. Aliphatic olefins dominate over aromatics in natural biota, where few aromatic or heterocyclic hydrocarbons are produced (NRC 1985). These identifying characteristics are extremely useful in determining marine and terrestrial biogenic inputs to the ocean. Biogenic hydrocarbons are expected to dominate all other inputs in clean (unaffected) oceanic areas.

In contrast to the relatively simple suite of hydrocarbons produced biologically, crude petroleum products contain a much more complex mixture of hydrocarbons having a much wider boiling (molecular weight) range. Petroleum contains several homologous series of compounds such as n-alkanes, cycloalkanes, and steranes that are not found in living organisms. The ratio of odd-to-even, carbon-number n-alkanes is very close to one. The non-biogenic isoprenoid, phytane, is commonly found in petroleum. Similarly, petroleum contains high concentrations of naphthenic, aromatic, and heterocyclic compounds, but very little olefinic material (NRC 1985). These characteristics make petroleum contamination fairly easy to distinguish from naturally produced biogenic compounds in the marine environment. (Interpreting the weathering history of hydrocarbons after they have entered the environment, however, is not as straightforward).

In some areas of the oceans, natural petroleum seepage from sediments into the overlying water column can present a major input source. Chemically, oil coming from the seep would have a composition similar to crude oil, as described above, and could easily be differentiated from natural biogenic sources. Although many crude oil seeps have been observed in the western Gulf of Mexico, no seeps have been reported in the eastern Gulf (NRC 1985). Because the likelihood of oil residues being transported from the western to eastern Gulf of Mexico is small, it is unlikely that natural seeps would contribute a significant amount of oil to the study area.

Major sources of anthropogenic hydrocarbons to coastal environments and estuaries include municipal and industrial waste and land runoff. According to the NRC (1985), approximately 36% of all hydrocarbon inputs to the ocean originate from these sources. Of these inputs, municipal wastewaters contribute about 60% of the petroleum hydrocarbons. Most of the population in the study area resides in the Florida Keys. Treated wastewater from the Keys is routinely discharged into the surrounding environment. Although secondary treatment removes most of the easily oxidizable organic matter from wastewater, this treatment does not remove many of the more refractory organics, including hydrocarbons. Because a major portion of the hydrocarbons in treated

wastewater seems to be of petroleum origin (NRC 1985), it should not be difficult to distinguish this input source from naturally produced biogenic compounds. Although there are no major cities along the Southwest Florida study area, there are population centers at Marco Island and in the Florida Keys, and treated wastewater discharged from cities farther north such as Naples and Fort Myers could conceivably be transported south to the study area. However, Van Vleet and Reinhardt (1983) have shown that municipal wastewater treatment plants located in subtropical environments may be much more efficient in breaking down hydrocarbons before the wastewater is discharged to the environment. Therefore, the actual contribution of hydrocarbons from municipal wastewaters to the study area is uncertain.

Industrial inputs also contribute hydrocarbons to the marine environment. These inputs can be from direct industrial losses or from incomplete combustion of fossil fuels. Hydrocarbon inputs from direct industrial discharges would be expected to chemically resemble crude or refined oil, and therefore be distinguishable from natural biogenic inputs (although they may not necessarily be distinguishable from other crude or refined oil inputs). Incomplete fossil fuel combustion products released from industrial stacks are chemically distinguishable from other petrochemical inputs based upon their polycyclic aromatic hydrocarbon alkyl homolog distributions. In undegraded petroleum, homologous series of substituted aromatic hydrocarbons occur. An example would be naphthalene plus its more abundant mono-, di-, tri-, and tetra-methyl naphthalene homologs. In fossil fuel combustion products, the unsubstituted (non-alkylated) parent compound (e.g., naphthalene) would dominate and the substituted homologs would either be absent or would be present in much lower concentrations. Therefore, if the proper analytical methodology is available, it is possible to investigate petrogenic versus pyrogenic hydrocarbon inputs to the environment. In the study area, direct industrial discharges would be expected to occur primarily in the Florida Keys. Fossil fuel combustion products, however, could originate a great distance from the study area and be transported in via the atmosphere and deposited.

Most automobile gasoline emissions produce relatively low molecular weight hydrocarbons that are not easily detected using conventional methodology. Crankcase oil leaking from automobile engines onto streets, however, could represent an eventual input source to coastal waters from land runoff. Again, inputs from this source would be expected mostly in areas proximate to the Florida Keys. Land runoff from the Everglades would be expected to contribute mainly biogenic hydrocarbons to the rest of the study area. There are no major river inputs to the study area, with the closest riverine input being the Caloosahatchee River/Charlotte Harbor system to the north. It has been shown that this system does not contribute major amounts of hydrocarbons to the study area (Pierce et al. 1986).

In the open ocean, including the Gulf of Mexico, anthropogenic hydrocarbon inputs originate mainly from oil transportation activities. These activities account for as much as 46% of the total petroleum hydrocarbon input to the oceans (NRC 1985). By far, most of this input arises from routine tanker operations (68% of this input) and tanker accidents (26% of this input). The remainder is released to the oceans from offshore production, marine terminals, dry-docking, and non-tanker accidents. Although no offshore production is currently taking place in or near the study area, tanker activity may play a major role in contributing petroleum hydrocarbons to the study area. Van Vleet et al. (1983a,b, 1984) have shown that most pelagic tar collected in the study area and throughout the eastern Gulf of Mexico probably originates from tanker discharges. Non-tanker accidents (i.e., oil well blowouts) should also be included as another potential major source of hydrocarbons to this area. A major disaster occurred in 1979 when the *Ixtoc-I* oil well blew out in the Bay of Campeche off Mexico, spilling approximately 500 million liters of crude oil into the southwestern Gulf over a period of nine

months before it was successfully capped (Atwood 1980). Although this spill did not significantly affect the South Florida study area, oil reached beaches of the western Gulf of Mexico, resulting in substantial cleanup costs (Restrepo et al. 1982). Development of production and shipping activity in the current study area could increase the likelihood of enhanced hydrocarbon inputs not only from oil well blowouts, but from each of the above transportation-related sources.

Hydrocarbon Distribution

Water Column

Once oil is released into the marine environment, early stages of weathering are dominated by evaporation and dissolution, resulting in a rapid loss of lower molecular weight n-alkanes, isoalkanes, cycloalkanes, and aromatics up to about C_{14}. According to data from the *Ixtoc-I* and *Ekofisk* oil well blowouts, as much as 50 to 60% of discharged crude oil can be lost to evaporation and dissolution within the first several hours (Haegh and Rossemyr 1980). Within one to two days, oil spilled into oceanic waters and subjected to enhanced wind and wave activity can form stable water-in-oil emulsions (mousse) that generally are dispersed only by long-term physical weathering processes (NRC 1985). If no mousse formation takes place, crude oil residues remaining after evaporation and dissolution processes stabilize contain higher molecular weight, more viscous hydrocarbons that congeal to form material commonly known as pelagic tar or tarballs. This tar undergoes further weathering processes such as dispersion (propulsion of oil droplets into the water column by breaking waves), microbial and chemical (photo/autoxidation) degradation, and sedimentation. In the long term, these latter processes determine the fate of tar residues in the ocean, with the average lifetime of a pelagic tarball being approximately one year (Butler et al. 1973; Butler 1975). Based upon these weathering processes, one would expect any oil found in the water to be present primarily in either the dissolved/dispersed phase or as pelagic tar. The following discussion will focus first on the occurrence of pelagic tar in the study area, and then on the occurrence of hydrocarbons in the dissolved/dispersed phase.

The most comprehensive study of pelagic tar along the Southwest Florida continental shelf was carried out from 1980 to 1982 as part of a larger project investigating pelagic tar in the entire eastern Gulf of Mexico (Van Vleet et al. 1983a,b, 1984). During this study, 416 surface and subsurface pelagic tar samples were collected during monthly cruises throughout the eastern Gulf. Tar was primarily associated with the Loop Current, whereas Florida's continental shelf areas were relatively uncontaminated (**Figure 3.1**). As the Loop Current exits the Gulf of Mexico through the Straits of Florida (i.e., between the Florida Keys and Cuba), pelagic tar contours become squeezed together and higher tar concentrations come in closer proximity to the shoreline. It has been shown that as currents carrying these high concentrations of tar exit through the Straits of Florida, eddies can frequently break off the Florida Current along the Southeast Florida coastline and move shoreward with a concomitant transport of tar to Florida beaches (Lee 1971, 1975; Lee and Mayer 1977; Williams et al. 1977). This suggestion is supported by exceptionally high concentrations of tar collected along beaches of Southeast Florida from Key West to Fort Pierce (Romero et al. 1981). Similar concentrations of beach tar and pelagic tar were observed in a separate study that extended these results to the Dry Tortugas (Zheng and Van Vleet 1988).

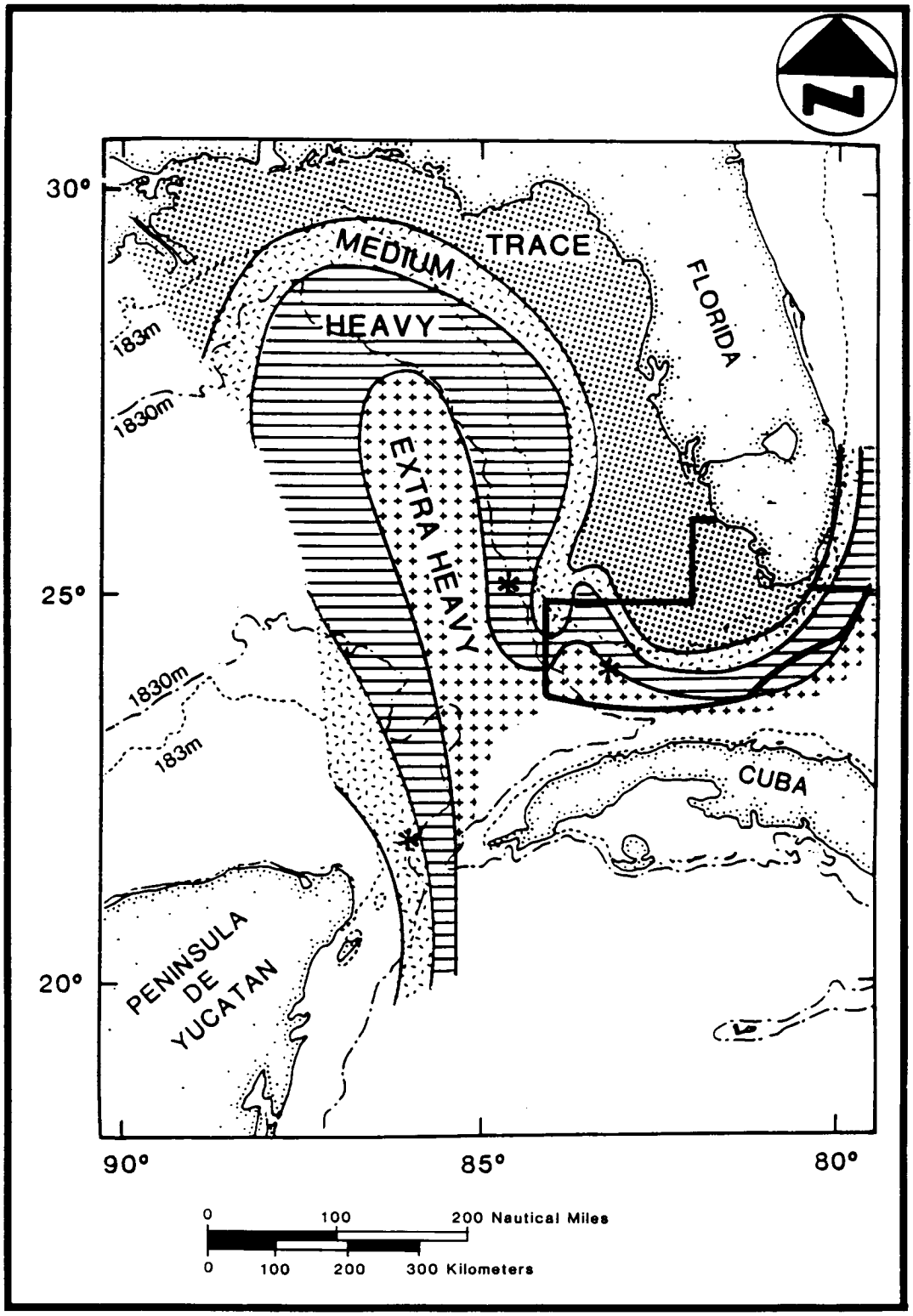

Figure 3.1. Distribution of pelagic tar in eastern Gulf of Mexico (Adapted from: Van Vleet et al. 1984). Dark, solid line near middle right outlines the current study area. Classification of tar follows Wang et al. (1976): Trace = <0.1 mg/m^2; Medium = 0.1 to 1.0 mg/m^2; Heavy = 1 to 5 mg/m^2; and Extra Heavy = >5 mg/m^2 (wet wt). Asterisks show stations where dissolved hydrocarbons were reported by Iliffe and Calder (1974); concentrations are reported in the text.

In the northern portion of the South Florida study area (i.e., primarily in Florida Bay), only trace concentrations of pelagic tar have generally been observed (i.e., <0.1 mg/m^2) (**Figure 3.1**). Water circulation in this area is not well defined; however, several studies indicate that currents are weak and variable with average flows of only 1 to 2 cm/s (Cooper 1982; Danek and Lewbel 1986; Environmental Science and Engineering, Inc. et al. 1987). Although the concentration of floating tar in this portion of the study area is low, any oil spilled into this area would have a relatively long residence time and would not be rapidly flushed out. Studies of beach tar collected along this area have shown only minor amounts of tar residues present (Romero et al. 1981). Beaches and offshore waters in this portion of the study area seem to be relatively pristine with respect to crude oil residues.

To the west of the Dry Tortugas and south of the Florida Keys, heavy to extra heavy tar concentrations (>5 mg/m^2) have commonly been observed (**Figure 3.1**). Although flow through the Straits of Florida is much faster than flow in Florida Bay, significant amounts of tar can be transported shoreward from the Straits of Florida by eddies as discussed above. It is the high concentrations of tar in this area that present a threat to Southeast Florida beaches. Much of the tar in the study area has been shown to originate from crude oil tanker discharges in the Gulf of Mexico (Van Vleet et al. 1983a,b, 1984). Although no other investigations of pelagic tar in the study area have been reported, results of the above studies have been summarized and compared with similar data collected throughout the Caribbean as part of the Intergovernmental Oceanographic Commissions's Caribbean Pollution (CARIPOL) research and monitoring program (Atwood et al. 1987a,b). Other CARIPOL pelagic tar data from the eastern Gulf of Mexico and the Caribbean Sea interface well with data reported for the study area.

The earliest work on dissolved and dispersed hydrocarbons in the eastern Gulf of Mexico was carried out by Iliffe and Calder (1974). These authors reported dissolved hydrocarbons from three stations in the eastern Gulf, one of which occurred in the study area (**Figure 3.1**). Although these dissolved hydrocarbons showed no depth-related trends, observed concentrations were highest in the Straits of Florida (range = 16 to 75 μg/L, average = 47 μg/L), i.e., the station within the South Florida study area. Concentrations at the other two stations ranged from 7 to 24 μg/L and averaged only 12 μg/L both northwest of the study area and in the Straits of Yucatan (**Figure 3.1**). In addition to dissolved hydrocarbons showing the highest total concentration in the study area, they also comprised the highest percentage of the total extractable lipid (TEL) material in this area (averaging 26% of TEL in the Straits of Florida versus 5 to 8% of TEL in the mid-Gulf and Straits of Yucatan). Qualitative hydrocarbon distributions were also different in the Straits of Florida. Although petroleum contamination could not be definitively assigned to these hydrocarbons, high petroleum discharge in the Gulf and complex hydrocarbon assemblages in the gas chromatographic data suggest this may have been an important source for dissolved hydrocarbons in this area. It is interesting to note that the highest dissolved hydrocarbon levels reported by Iliffe and Calder (1974) occurred in the same area where the pelagic tar data of Van Vleet et al. (1983a,b, 1984) showed high concentrations of tar nearest the Florida coastline, i.e., in the Straits of Florida south of the Florida Keys.

The most comprehensive study of dissolved and dispersed hydrocarbons in the eastern Gulf of Mexico and Straits of Florida was carried out by Atwood et al. (1987a,b) as part of the CARIPOL project mentioned above. During that study, 114 measurements of dissolved/dispersed hydrocarbons were made on water collected 1 m below the surface using hexane extraction and ultraviolet fluorescence against a chrysene standard. In Florida Bay, no dissolved/dispersed hydrocarbons could be detected. In the Straits of Florida below the Florida Keys, concentrations averaged 10.6 mg/L and were the highest

levels observed in the eastern Gulf of Mexico. Although the levels are higher than those reported by Iliffe and Calder (1974), the trends are unmistakably the same. Differences in these studies are thought to be due to differences in analytical methodology. Atwood et al. (1987b) reported that concentrations of dissolved/dispersed hydrocarbons and floating tar covaried ($r = 0.84$) for samples reported in their study. Although it is unlikely that weathered tar would contribute significantly to dissolved/dispersed petroleum hydrocarbon concentrations, the strong covariance of the two would implicate a fresh input from shipping and petroleum operations as a major contributor of hydrocarbons to the water column in this area (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1985; Atwood et al. 1987b).

Sediments

Although several comprehensive studies on the distribution of sedimentary hydrocarbons have been carried out along the northern and central West Florida continental shelf, very few data are available on hydrocarbon concentrations in sediments within the study area. The few data that are available from this area resulted primarily from the Southwest Florida Shelf Ecosystems Study (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1983, 1985; Continental Shelf Associates, Inc. 1987). This study was carried out in anticipation of offshore oil and gas exploration and development activities off Southwest Florida. Of the 29 stations sampled during this study, only about seven were actually within the South Florida study area, with the remainder being just to the north and northwest (**Figure 3.2**). For all stations of this three-year study, sedimentary hydrocarbon concentrations were low and were dominated by naturally produced biogenic compounds of mixed marine and terrestrial origin. Average hydrocarbon levels generally decreased going offshore, from values of about 1.6 μg/g in nearshore stations to about 0.2 μg/g beyond the 100-m isobath. Sediment samples collected during summer months averaged about 1.4 times higher than these levels due to higher seasonal productivity in the overlying water column. Within the South Florida study area, hydrocarbon concentrations averaged 1.5 μg/g during winter months and 2.6 μg/g at selected stations during summer.

Although total hydrocarbon concentrations are important in evaluating hydrocarbon inputs, additional parameters must be used to characterize the type of hydrocarbons present. Gas chromatographic fingerprinting of aliphatic and aromatic-olefinic hydrocarbon fractions from each sediment sample was made during the above Southwest Florida Shelf Ecosystem Study. Three major types of hydrocarbons could be distinguished by gas chromatographic analyses: (1) biogenic hydrocarbons of marine origin containing nC_{17}, pristane, a cycloalkane with retention index 2085, and no unresolved complex mixture; (2) biogenic hydrocarbons of mixed marine and terrigenous origin, including the above aspects plus nC_{29}, a homologous n-alkane series showing a carbon preference index (CPI) >1, and containing olefinic rather than aromatic compounds; and (3) the above mixture of biogenic marine and terrigenous compounds plus petrogenic hydrocarbons with an n-alkane CPI = 1, and containing a relatively large proportion of aromatic compounds relative to olefinic (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1983). Based upon these criteria, all but one of the sediments analyzed during the above study were of marine biogenic or mixed marine-terrigenous biogenic origin (**Figure 3.2**). In the study area, there were no stations that showed any evidence of significant petroleum contamination. However, combined high resolution gas chromatography and mass spectrometry analyses of selected extracts from these stations showed a ubiquitous but very low level of aromatic hydrocarbon input. These aromatics seemed to be of mixed source with some being produced by fossil fuel combustion processes and others originating from direct petroleum input. Nonetheless, the very low levels of these aromatic compounds (1 to 5 ng/g) did not constitute a significant amount of hydrocarbon contamination to this area.

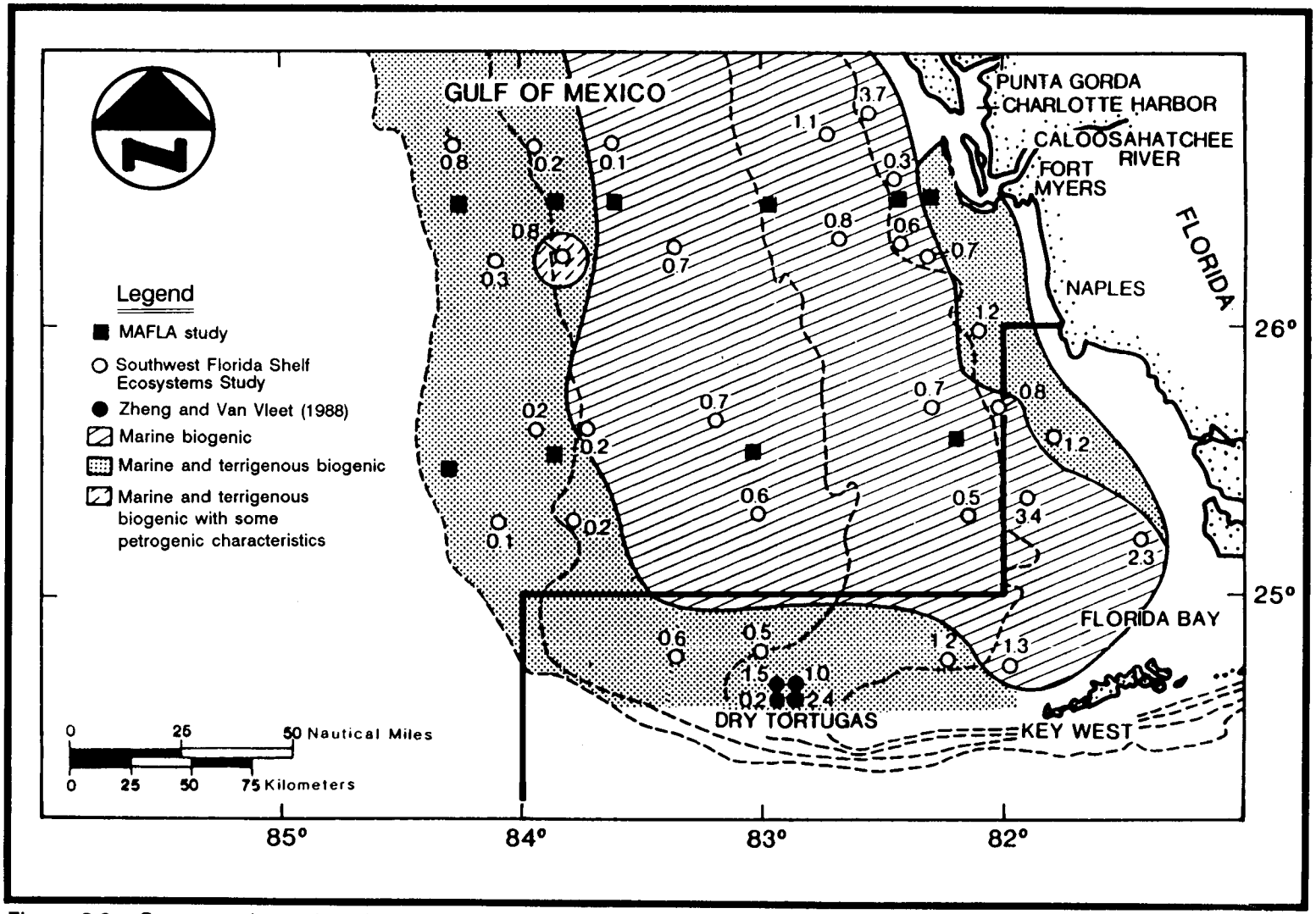

Figure 3.2. Concentrations of sedimentary hydrocarbons reported for the Southwest Florida continental shelf. Concentrations (indicated by numbers next to stations) are in μg total hydrocarbons/g dry wt sediment. Dark solid line to lower right outlines the current study area.

The only other sedimentary hydrocarbon data reported for the South Florida study area are from four stations in the Dry Tortugas during mid-summer and reported by Zheng and Van Vleet (1988). Total hydrocarbon concentrations at these stations ranged from 0.2 to 2.4 μg/g and were dominated by a mixed marine/terrigenous biogenic input (**Figure 3.2**). There was no evidence of petroleum contamination in sediments from these stations. These hydrocarbon levels agree well with those reported from summer samples collected during the Southwest Florida Shelf Ecosystems Study. Hydrocarbon levels reported throughout the study area also agree well with other sedimentary hydrocarbon data reported from farther north along the West Florida continental shelf (Gearing et al. 1976; Alexander et al. 1977; Boehm 1978; Overton and Laseter 1980). Because hydrocarbon levels in the South Florida study area are very low and dominated by biogenic components, any significant future hydrocarbon input to the study area should be readily apparent and easily detectable.

Organisms

No data are available on hydrocarbons in marine organisms from the study area. The closest set of biological samples analyzed for hydrocarbons were collected during the 1975 to 1978 MAFLA study from just north of the study area (**Figure 3.2**). Hydrocarbon compositions were investigated during the MAFLA study in selected benthic organisms and zooplankton (Alexander et al. 1977; Dames & Moore 1979). Analysis of muscle tissue from the demersal fish *Syacium papillosum* exhibited primarily biogenic hydrocarbons with no definitive evidence for petroleum contamination. Macroepifauna consisting of various shrimp, crabs, bivalve molluscs, and echinoderms were also analyzed for hydrocarbon content and again showed no petroleum contamination but demonstrated a wide variation in specific branched and olefinic compounds indicative of marine biogenic and diagenetic hydrocarbons (Dames & Moore 1979). Hydrocarbons in zooplankton showed seasonal changes most likely reflecting uptake from phytoplankton. Pristane was the most abundant compound, along with a group of peaks centering around a Kovats Index of 2080 (Dames & Moore 1979). The lack of petrogenic contamination in biota indicates the absence of petrogenic hydrocarbons in the water column as well as in sediments. This again reflects the pristine nature of the South Florida study area north of the Florida Keys.

Transport and Transfer Processes

Physical and Chemical Processes

Hydrocarbons can be transported to and transferred throughout the marine environment by a variety of physical and chemical processes (**Table 3.11**). One mechanism for transporting both natural and anthropogenic hydrocarbons to the oceans is by atmospheric transport followed by dry or wet deposition. Zimmerman (1979) has shown that volatilization of naturally produced hydrocarbons from living and non-living terrestrial plants can result in release of substantial quantities of biogenic hydrocarbons (aromatics, methane, olefins, paraffins, and terpenes) to the atmosphere where they can then be dispersed over the oceans and deposited. Most of these volatiles are relatively low molecular weight ($<C_{12}$) and would remain soluble after deposition in the oceans. Heavier molecular weight hydrocarbons ($>C_{12}$) have also been shown to be transported atmospherically and deposited in the oceans (Simoneit 1977). These insoluble compounds may then enter the food chain or be transported by other physical processes as discussed below. Hydrocarbons emitted to the atmosphere by industrial processes can be similarly transported to the ocean via the atmosphere. The Everglades could potentially provide a major input of biogenic hydrocarbons via the atmosphere to the study area. Industrial activity in the Florida Keys could also provide an input of hydrocarbons by this pathway.

Hydrocarbons could also be transported to the study area by direct discharge from shipping activities, industrial inputs, and by rivers and land runoff (although no major rivers discharge directly into the study area, the Charlotte Harbor-Caloosahatchee River System is just to the north and provides a potential source). Of these direct discharges, shipping activity probably represents the greatest potential hydrocarbon source to the study area. It has been estimated that between 67 and 333 million metric tons of crude oil are shipped through the Straits of Florida annually (U.S. Coast Guard 1976; Reinburg 1984; South Florida Regional Planning Council 1984). Assuming a conservative loss of 1/30,000 of the transported oil (NRC 1985), this would result in a loss of between 2,200 and 11,100 metric tons of crude oil discharged from these ships while in transit annually. Clearly not all of this oil is released into the study area, but if only 0.1% were discharged here, it would still represent between 2.2 to 11.1 metric tons of oil released near the study area annually. Certainly this could represent a major pathway for hydrocarbon input to this area. Van Vleet et al. (1983a,b, 1984) have shown that most floating tar in this area originates from tanker operations.

Table 3.11. Potential transport and transfer processes of hydrocarbons in the marine environment.

PHYSICAL AND CHEMICAL PROCESSES
Atmospheric Transport
Direct Discharge
Evaporation
Dissolution
Spreading
Advection
Emulsification
Dispersion
Photo/Auto-oxidation
Sedimentation
BIOLOGICAL PROCESSES
Microbial Degradation
Adsorption
Uptake
Storage
Metabolism
Release

When fresh oil is spilled or discharged into the ocean, a large percentage is rapidly transferred away by dissolution and evaporation. These processes are often difficult to differentiate due to their similar thermodynamic properties, although evaporation often occurs orders of magnitude faster and therefore dominates early losses of oil by these processes (NRC 1985). As much as two-thirds of a spill may be lost due to evaporation or dissolution within a matter of hours or days. Hydrocarbons dissolved into the water are particularly important, due to their known toxicity to biological systems. Residual oil that remains after these processes stabilize presents environmental consequences of its own (fouling of beaches, uptake by organisms, etc.).

Further transport of the remaining spilled oil is largely due to two processes: spreading and advection. Spreading of oil results from a dynamic equilibrium established between the forces of gravity, inertia, friction, viscosity, and surface tension (NRC 1985). Although small spills of light oil may spread to monolayer thickness, it is unlikely that a large crude oil spill will become less than several millimeters to centimeters thick. As the oil spreads, evaporation and dissolution of low molecular weight components occur, leaving the heavier, more viscous, and non-spreading components. Once the spreading rate of an oil spill declines, advective processes begin to dominate.

Advection is due to the influence of overlying winds and/or underlying currents, and is responsible for such processes as emulsification, dispersion, and lateral transport (NRC 1985). Wind mixing of spilled oil with seawater often results in stable water-in-oil emulsions being formed. These are commonly referred to as mousse. Although mousse formation depends upon several physico-chemical parameters, these emulsions are more commonly formed in spills of heavy crude oils rather than spills of light distillates. Once stabilized, these mousse formations are quite resistant to chemical or biological degradation. Advection by breaking waves is often responsible for

dispersion of spilled oil into the water column, with subsequent breaking up of the oil spill into smaller patches. Dispersion also results in the introduction of "particulate" phase oil to organisms living in subsurface waters. Large drops of oil driven down into the water column may rise and coalesce with the main slick. Small oil droplets may be entrained in subsurface eddies and become permanently incorporated into the water column.

Advection is also responsible for the lateral transport of oil by current and eddy systems. Transport of dissolved and particulate hydrocarbons in the eastern Gulf of Mexico has been well documented (Van Vleet et al. 1983a,b, 1984; Atwood et al. 1987a,b). According to Van Vleet et al. (1984), approximately 10 to 50% of floating tar in the eastern Gulf is transported from the Caribbean Sea through the Straits of Yucatan by the Yucatan Current. The remaining floating oil (50 to 90%) originates within the Gulf and is transported throughout the eastern Gulf by the Loop Current and then carried out of the Gulf through the Straits of Florida. Currents seem to play a major role in influencing the transport of spilled oil to and from the study area.

Both dissolved and "particulate" fractions of spilled oil are subject to photo-oxidation and/or auto-oxidation. These chemical oxidative processes result in formation of polar byproducts such as aldehydes, esters, hydroperoxides, ketones, organic acids, phenols, and sulfoxides. Formation of these products results in darkening of the oil, increased ease of emulsification, increased solubility, and oftentimes increased toxicity (NRC 1985). Although photo-oxidation seems to be minor with respect to total mass balance considerations, it produces significant changes in the chemical properties of the exposed oil, thereby altering its physico-chemical behavior and transport in the oceans. Auto-oxidation results from the thermodynamic instability of reduced carbon compounds in the presence of free radical reactants. Products formed are similar to those produced during photo-oxidation and may therefore play a role in physical and chemical transfer processes of the oil.

The final physical process important in the transport of oil in the oceans is sedimentation. Various forms of oil in the ocean can be readily sorbed onto settling particles and transported vertically through the water column with eventual incorporation into bottom sediments. Similarly, floating or dispersed oil globules can adsorb particulate material, thereby increasing their density and leading to eventual sedimentation. It is unlikely that even weathered oil will sink on its own accord without adsorption of more dense particulates. Field investigations of actual spills have estimated that approximately 1 to 10% of spilled oil is transported to the bottom via sedimentation processes. Sedimentation by incorporation into biogenic fecal pellets (as discussed below) is also an important vertical transport mechanism. In the South Florida study area, vertical transport of hydrocarbons from the water column to the sediments would be expected to proceed primarily by these pathways.

Biological Processes

Processes that are important in the biological alteration and transport of hydrocarbons in the marine environment are listed in **Table 3.11.** In general, biological processes affecting the distribution of hydrocarbons can be divided into two categories: microbial processes, and other eukaryotic processes (including both invertebrates and vertebrates).

Microbial processes include those carried out by bacteria, yeasts, and fungi. Although degradation by yeasts and fungi has been shown to be significant, bacterial degradation is probably the most important microbial process on a global scale. Biogenic hydrocarbons produced both in marine and terrestrial environments contain a

rather simple suite of compounds that can be degraded relatively easily by bacteria. In some cases, terrestrial hydrocarbon inputs are protected by a waxy or pollen-type matrix and are more resistant to microbial attack. Nonetheless, most of these compounds are non-toxic and can persist in the environment for weeks, months, or years. Petroleum hydrocarbons, on the other hand, are comprised of many thousands of compounds that differ widely in terms of their biodegradability. Alkanes, alkenes, and simple mono-aromatics can be degraded relatively quickly, while tars and resins are virtually impervious to biological attack (NRC 1985). Between these two extremes, petroleum contains a wide range of compounds of intermediate degradability. Generally, microbial degradation of n-alkanes is most rapid, followed by simple aromatics, then isoalkanes, cyclo-alkanes, and condensed aromatics. Higher molecular weight (condensed) aromatics, tars, and resins may remain undegraded in the environment for decades. The most common type of primary metabolic attack by microorganisms is mediated by mixed function oxidases (cytochrome P450 and rubredoxin) (NRC 1985). This results in the eventual loss of hydrocarbon material by the formation and release of short-chain acids and other byproducts. In the case of higher molecular weight aromatics, metabolic products formed by microbial alteration may be more toxic than their original precursors.

Higher organisms, including both micro- and macro-vertebrates and invertebrates, affect the transport of hydrocarbons in several different ways (**Table 3.11**). In the most simple case, dissolved hydrocarbons may be adsorbed onto the exterior of an organism and transported downwards through the water column after an organism dies. Alternatively, dissolved and particulate hydrocarbons may be actively taken up either by direct ingestion or by uptake with water or foodstuff. Once ingested, hydrocarbons can be stored within the organism, metabolized, or released. If stored (generally in lipid-rich tissues), hydrocarbons can be passed through the food web to other organisms. Upon death of the organism, stored hydrocarbons can be transported downwards through the water column and deposited in sediments. Hydrocarbons can also be metabolized by higher organisms with subsequent storage or release of the metabolic byproducts. Many marine vertebrates and invertebrates metabolize hydrocarbons via the cytochrome P450 mixed function oxidase pathway (NRC 1985).

Perhaps the main mechanism by which higher organisms affect the distribution of hydrocarbons in the oceans is by transport through the water column by fecal pellets. Forrester (1971) first reported that oil droplets mixed downward into the water column were generally of the size range of natural food particles taken up by zooplankton. Much oil taken up by zooplankton and other pelagic organisms is incorporated into fecal pellets in a relatively unmodified condition, then excreted and transported downwards through the water column where it can become incorporated into sediments or acted upon by bacteria.

Another mechanism of hydrocarbon release is depuration. If an organism has accumulated hydrocarbons in a contaminated area, removal of the organism to a clean area (or removal of the contaminant from the exposed area) allows the organism to release, or depurate, some of the accumulated hydrocarbons from its tissues. Although depuration of hydrocarbons accumulated under laboratory conditions occurs fairly rapidly (i.e., within a few days), organisms collected from heavily contaminated areas or from areas exposed to long-term inputs require much longer time periods for depuration, which even then is incomplete (NRC 1985).

In the study area, the primary mechanisms by which marine organisms would be expected to affect the transport or transfer of hydrocarbons would be by microbial degradation or fecal pellet transport. In subtropical systems where higher temperatures result in higher metabolic rates, degradation of hydrocarbons may proceed more rapidly than in temperate or polar regions. Little work has been carried out in this area.

Nonetheless, in the event of a major oil spill, the rates of degradation or fecal transport would be much slower than the time required for the oil to have a detrimental impact on the area's biota (Burns and Knap 1989; Jackson et al. 1989).

Conclusions

Investigations of hydrocarbons in sediment, water, and biota of the study area have shown that this region is relatively free from petroleum contamination, with the exception of floating and dissolved oil residues in the Straits of Florida. Certainly the Florida Bay portion of the study area appears relatively pristine. Unlike biota of the western and northern Gulf of Mexico, flora and fauna of the Southwest Florida shelf have not been exposed to chronic petroleum contamination. The possibility for stress from a sudden influx of petroleum hydrocarbons is, therefore, of concern. Of particular concern are such unique and ecologically important communities as coral reefs, mangroves, and seagrasses (see **Chapter 15**).

Unfortunately, little is known about the persistence or effects of oil spills in subtropical/tropical environments. Although the probability of a major spill occurring in the area may be small, continuous low-level inputs may occur if oil and gas development and transportation activities are initiated. Little is known about how continuous low-level inputs can affect an ecological system. Most studies that have been carried out have concerned high-level, acute exposures that might be expected from a more severe spill. How effects from low-level, chronic inputs would compare with those from larger, acute inputs is still largely unknown. Furthermore, few data are available on present levels of hydrocarbons in marine organisms from the study area. More information on these levels would certainly help in evaluating future effects.

It is unclear how oil spilled into Florida Bay would be dispersed or transported within or away from the study area. Some information on oil spill trajectories is presented in **Chapter 12**. However, more detailed physical oceanographic data would allow better prediction of the fate of oil spilled in the study area.

Another topic with very limited information concerns degradation rates of oil in tropical/subtropical environments. Due to higher average temperatures and greater incident sunlight, both metabolic degradation and photo-oxidation rates would be expected to be enhanced in these areas. More studies are necessary to substantiate this hypothesis.

Although little of the above information is available for the study area, studies from other subtropical/tropical systems provide useful information for comparison. One oil spill that occurred in Panama's coastal waters is particularly revealing. In April 1986, an estimated 8 million liters of crude oil leaked from a Panamanian coastal refinery and washed ashore along a 10-km (5.4-nmi) stretch of Panama's coastline (Burns and Knap 1989; Jackson et al. 1989; see also **Chapter 15**). It was the largest recorded spill into tropical or subtropical waters. Documentation of the spread of oil, its chemical transformations, and its biological effects began immediately and is continuing. Intertidal mangroves, seagrasses, algae, and associated invertebrates were covered with oil and died soon after the spill. Most mangroves affected by oil died within three months (Rogers 1989a,b); however, die-off was still occurring after more than a year. After three years, oil slicks are still leaching from the dead mangroves. It is estimated that replanted mangroves will take more than 50 years to reach the size of those killed by the 1986 spill. In addition, there was also an extensive and unexpected mortality of shallow subtidal reef corals, which will likely need hundreds of years to fully recover (see **Chapter 15**). This is an example of the type of damage that could occur in the study area. One major difference between the Panama spill site and the study area is

that the Panama site had a long history of environmental abuse due to dredging, landfilling, pesticide spraying, and refinery discharge (Jackson et al. 1989). In contrast, much of the study area along Southwest Florida has remained relatively pristine, as indicated by the data presented in this chapter. The fact that the Panama spill could have such devastating consequences in an area already accustomed to environmental degradation suggests that the more pristine Southwest Florida area could be affected even more severely. Therefore, if offshore drilling and shipping activities are further developed in this area, it is important for them to be carried out with as much concern for potential environmental consequences as possible.

REFERENCES CITED

Alexander, J. E., T. T. White, K. E. Turgeon, and A. W. Blizzard. 1977. *Baseline monitoring studies, Mississippi, Alabama, Florida outer continental shelf, 1975-1976.* Final report submitted to the U.S. Department of the Interior, Bureau of Land Management. Contract 08550-CT5-30.

American Public Health Association. 1976. *Standard methods for the examination of water and wastewater.* Washington, DC.

Atwood, D. K. 1980. *Preliminary results from the September 1979 RESEARCHER/PIERCE IXTOC-I Cruise.* Proceedings of a symposium held in Key Biscayne, Florida, June 9-10, 1980. National Oceanic and Atmospheric Administration. Boulder, CO.

Atwood, D. K., F. J. Burton, J. E. Corredor, G. E. Harvey, A. J. Mata-Jimenez, A. Vasquez-Botello, and B. A. Wade. 1987a. Results of the CARIPOL petroleum pollution monitoring project in the wider Caribbean. *Mar. Pollut. Bull.* 18:540-548.

Atwood, D. K., S. Dinkel-McKay, G. C. Romero, and E. S. Van Vleet. 1987b. Floating tar and dissolved/dispersed petroleum hydrocarbons in the northern Gulf of Mexico and the Straits of Florida. *Caribb. J. Sci.* 23:73-76.

Boehm, P. D. 1978. Interpretation of sediment hydrocarbon data. In *The Mississippi, Alabama, Florida outer continental shelf baseline environmental survey, 1977/1978, Vol. II-A.* Final report submitted to the U.S. Department of the Interior, Bureau of Land Management, 572-607. New Orleans. Contract AA550-C77-34.

Bowen, H. J. M. 1979. *Environmental chemistry of the elements.* New York: Academic Press.

Boyle, E. A., D. F. Reid, S. S. Huested, and J. Hering. 1984. Trace metals and radium in the Gulf of Mexico: An evaluation of river and continental shelf sources. *Earth Planet. Sci. Lett.* 69:69-87.

Brooks, J. M., T. L. Wade, E. L. Atlas, M. C. Kennicutt II, B. J. Presley, R. R. Fay, E. N. Powell, and G. Wolff. 1988. *Analyses of bivalves and sediments for organic chemicals and trace elements from Gulf of Mexico estuaries.* Second annual report to the National Oceanic and Atmospheric Administration, National Status and Trends Program. Contract 50-DGNC-5-00262.

Bruland, K. W. 1983. Trace elements in sea water. In *Chemical Oceanography, Vol. 8,* ed. J. P. Riley and R. Chester, 157-220. New York: Academic Press.

Buat-Menard, P. 1986. *The role of air-sea exchange in geochemical cycling.* Boston: D. Reidel Publ. Co.

Burns, K. A., and A. H. Knap. 1989. The Bahia las Minas oil spill. Hydrocarbon uptake by reef building corals. *Mar. Pollut. Bull.* 20(8):391-398.

Butler, J. N. 1975. Evaporative weathering of petroleum residues: The age of pelagic tar. *Mar. Chem.* 3:9-21.

Butler, J. N., B. F. Morris, and J. Sass. 1973. *Pelagic tar from Bermuda and the Sargasso Sea.* Spec. Publ. Bermuda Biol. Stn. Res. No. 10.

Chesher, R. H. 1975. Biological impact of a large-scale desalination plant at Key West, Florida. In *Tropical marine pollution,* ed. E. J. F. Wood and R. E. Johannes, 99-153. New York: Elsevier.

Church, T. M., J. N. Galloway, T. D. Jickells, and A. H. Knap. 1982. The chemistry of western Atlantic precipitation at the mid-Atlantic coast and on Bermuda. *J. Geophys. Res.* 87(C13):11013-11018.

Collins, G. A. 1975. *Geochemistry of oilfield waters.* New York: Elsevier.

Continental Shelf Associates, Inc. 1987. *Southwest Florida shelf regional biological communities survey. Year 3 final report, Vol. II.* OCS Study MMS 86-0109. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Cooper, C. 1982. *Southwest Florida shelf circulation model, Vol. 1.* New Orleans: U.S. Department of the Interior, Minerals Management Service. Contract AA851-CTO-72.

Curtis, W. F., J. K. Culbertson, and E. B. Chase. 1973. *Fluvial sediment discharge to the ocean from the coterminous United States.* U.S. Geol. Surv. Circ. No. 670.

Dames & Moore. 1979. *The Mississippi, Alabama, Florida outer continental shelf baseline environmental survey 1977/1978.* New Orleans: U.S. Department of the Interior, Bureau of Land Management. Contract AA550-CT7-34.

Danek, L. J., and G. S. Lewbel, ed. 1986. *Southwest Florida shelf benthic communities study. Year 5 annual report, vol. II.* OCS Study MMS 86-0075. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Environmental Science and Engineering, Inc., LGL Ecological Research Associates, Inc., and Continental Shelf Associates, Inc. 1987. *Southwest Florida shelf ecosystems study, Vol. II.* OCS Study MMS 87-0023. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Forrester, W. D. 1971. Distribution of suspended oil particulates following the grounding of the tanker *Arrow.* *J. Mar. Res.* 29:151-170.

Garrels, R. M., and F. T. Mackenzie. 1971. *Evolution of sedimentary rocks.* New York: Norton and Co.

Gearing, P., J. N. Gearing, T. F. Lytle, and J. S. Lytle. 1976. Hydrocarbons in 60 northeast Gulf of Mexico shelf sediments: A preliminary survey. *Geochim. Cosmochim. Acta* 40:1005-1017.

Gilio, J. L., and D. A. Segar. 1976. *Biogeochemistry of trace elements in Card Sound, Florida: Inventory and annual turnover.* Univ. of Miami Sea Grant Program Spec. Rep. No. 5.

Haegh, T., and L. I. Rossemyr. 1980. A comparison of weathering processes of oil from the BRAVO and the IXTOC-I blowouts. In *Proceedings, Offshore Technology Conference, 1980*, 237-245. Houston, TX.

Heatwole, D. W. 1987. *Water quality assessment of five selected pollutant sources in Marathon, Florida Keys. Florida Keys monitoring study: 1984-1985*. Florida Department of Environmental Regulation, South Florida District, Marathon, FL.

Iliffe, T. M., and J. A. Calder. 1974. Dissolved hydrocarbons in the eastern Gulf of Mexico Loop Current and the Caribbean Sea. *Deep-Sea Res.* 21:481-488.

Jackson, J. B. C., J. D. Cubit, B. D. Keller, V. Batista, K. Burns, H. M. Caffey, R. L. Caldwell, S. D. Garrity, C. D. Getter, C. Gonzalez, H. M. Guzman, K. W. Kaufmann, A. H. Knap, S. C. Levings, M. J. Marshall, R. Steger, R. C. Thompson, and E. Weil. 1989. Ecological effects of a major oil spill on Panamanian coastal marine communities. *Science* 243:37-44.

Lapointe, B. E. 1989. Caribbean coral reefs: Are they becoming algal reefs? *Sea Front.* 35(2):84-91.

Lapointe, B. E., and J. D. O'Connell. 1988. *The effects of on-site sewage disposal systems on nutrient relations of groundwaters and nearshore waters of the Florida Keys*. Report prepared for the National Oceanic and Atmospheric Administration (Office of Coastal Zone Management), Florida Department of Environmental Regulation, and Monroe County, FL.

Lee, T. N. 1971. Oceanographic features of nearshore waters on a narrow continental shelf. In *Limitations and effects of waste disposal on an ocean shelf*, 105-170. Washington, DC: U.S. Environmental Protection Agency, Water Pollution Control Res. Ser. 10697EFG.

Lee, T. N. 1975. Florida Current spin-off eddies. *Deep-Sea Res.* 22:753-765.

Lee, T. N., and D. Mayer. 1977. Low-frequency current variability and spin-off eddies on the shelf off Southeast Florida. *J. Mar. Res.* 35:193-220.

Leifeste, D. K. 1974. *Dissolved solids discharge to the ocean from the coterminous United States*. U.S. Geol. Surv. Circ. No. 685.

Manker, J. P. 1975. Distribution and concentration of mercury, lead, cobalt, zinc and chromium in suspended particulates and bottom sediments - Upper Florida Keys, Florida Bay and Biscayne Bay. Ph.D. diss., Rice Univ., Houston, TX.

Mathis, J. M. 1973. Red mangrove decomposition: A pathway for heavy metal enrichment in Everglades estuaries. Master's thesis, Florida State Univ.

National Research Council. 1983. *Drilling discharges in the marine environment*. Washington, DC: National Academy Press.

National Research Council. 1985. *Oil in the sea: Inputs, fates, and effects*. Washington, DC: National Academy Press.

Nelsen, T. A., and J. H. Trefry. 1986. Pollutant-particle relationships in the marine environment: A study of particles and their fate in a major river-delta-shelf system. *Rapp. P.-V. Réun. CIEM* 186:115-127.

Overton, E. B., and J. L. Laseter. 1980. Distribution of aromatic hydrocarbons in sediments from selected Atlantic, Gulf of Mexico, and Pacific outer continental shelf areas. In *Petroleum in the marine environment*, ed. L. Petrakis and F. T. Weiss, 327-341. Washington, DC: American Chemical Society.

Pierce, R. H., R. C. Brown, E. S. Van Vleet, and R. M. Joyce. 1986. Hydrocarbon contamination from coastal development. In *Organic marine geochemistry*, ed. M. L. Sohn, 229-246. Washington, DC: American Chemical Society.

Presley, B. J., J. H. Trefry, and R. E. Shokes. 1980. Heavy metal inputs to Mississippi Delta sediments: A historical view. *Water, Air, Soil Pollut.* 14(4):481-494.

Reinburg, L. 1984. *Waterborne trade of petroleum and petroleum products in the wider Caribbean region*. Final report submitted to the U.S. Department of Transportation, Office of Marine Environment and Systems. Washington, DC. Contract DTCG-23-84-C-40018.

Restrepo, C. E., F. C. Lamphear, C. A. Gunn, R. B. Ditton, J. D. Nichols, and L. S. Restrepo. 1982. *Ixtoc I oil spill economic impact*. New Orleans: U.S. Department of the Interior, Bureau of Land Management. NTIS Nos. PB82-217860, PB82-217852, and PB82-217878.

Robblee, M. B., J. T. Tilmant, and J. Emerson. 1989. Quantitative observations on salinity. *Bull. Mar. Sci.* 44(1):523.

Rogers, D. K. 1989a. 1986 spill gives timely oil lesson. *St. Petersburg Times*, 14 June 1989, p. 1A.

Rogers, D. K. 1989b. If the big spill hits Florida. *St. Petersburg Times*, 21 June 1989, p. 1B.

Romero, G. C., G. R. Harvey, and D. K. Atwood. 1981. Stranded tar on Florida beaches. *Mar. Pollut. Bull.* 12:280-284.

Segar, D. A., and R. E. Pellenbarg. 1973. Trace metals in carbonate and organic rich sediments. *Mar. Pollut. Bull.* 4: 138-142.

Shiller, A. M., and E. A. Boyle. 1983. Trace metals in the plume of the Mississippi Rivers. *Eos Trans. Am. Geophys. Union* 64:1021 (Abstract).

Simoneit, B. R. T. 1977. Organic matter in eolian dusts over the Atlantic Ocean. *Mar. Chem.* 5:443-464.

Skinner, R. H. 1988a. Water quality results after C-111 freshwater release, John Pennekamp Coral Reef State Park. Unpubl. memorandum, Florida Department of Natural Resources.

Skinner, R. H. 1988b. Unpubl. memorandum to Jim Stevenson, Florida Department of Natural Resources, Dec. 8, 1988.

Skinner, R. H., and W. C. Jaap. 1986. *Trace metals and pesticides in sediments and organisms in John Pennekamp Coral Reef State Park and Key Largo National Marine Sanctuary*. Unpubl. draft report to the Florida Department of Environmental Regulation, Coastal Zone Management Office.

Slowey, J. F., and D. W. Hood. 1971. Cooper, manganese and zinc concentrations in Gulf of Mexico waters. *Geochim. Cosmochim. Acta* 35:121-138.

South Florida Regional Planning Council. 1984. *OCS facility siting study*. Miami, FL.

Spencer, M. J., S. R. Piotrowicz, and P. R. Betzer. 1982. Concentrations of cadmium, lead, and zinc in surface waters of the northwest Atlantic Ocean - a comparison of Go-flo and Teflon water samplers. *Mar. Chem.* 11:403-410.

Taylor, S. R., and S. M. McClennan. 1985. *The continental crust: Its composition and evolution*. Boston: Blackwell Scientific Publications.

Trefry, J. H., and B. J. Presley. 1976. Heavy metal transport from the Mississippi River to the Gulf of Mexico. In *Marine pollutant transfer*, ed. H. L. Windom and R. A. Duce, 39-76. Boston: D.C. Heath and Co.

Trefry, J. H., and B. J. Presley. 1982. Manganese fluxes from Mississippi Delta sediments. *Geochim. Cosmochim. Acta* 46:1715-1726.

Trefry, J. H., A. D. Fredricks, S. R. Fay, and M. L. Byington. 1978. *Heavy metal analysis of bottom sediments.* Final report to the U.S. Department of the Interior, Bureau of Land Management.

U.S. Coast Guard. 1976. *Vessel traffic study of the Straits of Florida.* Miami, FL.

U.S. Environmental Protection Agency. 1987. *Report to the Congress on ocean pollution.* EPA 530SW/88-003. Washington, DC.

Van Vleet, E. S., and S. B. Reinhardt. 1983. Inputs and fates of petroleum hydrocarbons to a subtropical marine estuary. *Environ. Int.* 9:19-26.

Van Vleet, E. S., W. M. Sackett, F. F. Weber, Jr., and S. B. Reinhardt. 1983a. Spatial and temporal variation of pelagic tar in the eastern Gulf of Mexico. In *Advances in organic geochemistry, 1981*, ed. M. Bjoroy, 362-368. London: John Wiley.

Van Vleet, E. S., W. M. Sackett, F. F. Weber, Jr., and S. B. Reinhardt. 1983b. Input of pelagic tar into the northwest Atlantic from the Gulf Loop Current: Chemical characterization and its relationships to weathered IXTOC-I oil. *Can. J. Fish. Aquat. Sci.* 40:12-22.

Van Vleet, E. S., W. M. Sackett, S. B. Reinhardt, and M. E. Mangini. 1984. Distribution, sources, and fates of floating oil residues in the eastern Gulf of Mexico. *Mar. Pollut. Bull.* 15:106-110.

Williams, J., W. F. Grey, E. B. Murphy, and J. J. Crane. 1977. Drift bottle analyses of eastern Gulf of Mexico surface circulation. In *Memoirs of the Hourglass Cruises, Vol. IV*, 1-134. St. Petersburg: Florida Department of Natural Resources.

Windom, H. L. 1980. Comparison of atmospheric and river transport of trace elements to the continental shelf environment. In *River input to ocean systems*, ed. J. M. Martin, J. D. Burton, and D. Eisma, 360-369. Paris: UNEP/UNESCO.

Windom, H., E. Taylor, and R. Stickney. 1973. Mercury in North Atlantic plankton. *J. Cons. CIEM* 35(1):18-21.

Wong, C. S., D. R. Green, and W. J. Cretney. 1976. Distribution and source of tar on the Pacific Ocean. *Mar. Pollut. Bull.* 7:102-106.

Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1983. *Southwest Florida shelf ecosystems study - Year 1.* New Orleans: U.S. Department of the Interior, Minerals Management Service.

Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1985. *Southwest Florida shelf ecosystems study - Year 2.* New Orleans: U.S. Department of the Interior, Minerals Management Service.

Zheng, W., and E. S. Van Vleet. 1988. Petroleum hydrocarbon contamination in the Dry Tortugas. *Mar. Pollut. Bull.* 19:134-136.

Zimmerman, P. R. 1979. *Determination of emission rates of hydrocarbons from indigenous species of vegetation in the Tampa/St. Petersburg, Florida area.* Final report submitted to the U.S. Environmental Protection Agency. Atlanta, GA. Contract 68-01-4432.

CHAPTER 4
COASTAL AND NEARSHORE COMMUNITIES

Samuel C. Snedaker (Mangrove Forests)
Walter C. Jaap and Pamela Hallock (Coral Reefs)
Joseph C. Zieman (Seagrass Beds)

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INTRODUCTION

To the south of the Florida peninsula lies a unique State and National treasure: a subtropical ecosystem of mangrove forests, coral reefs, and seagrass beds. South Florida is the only place in North America where this combination of rich natural communities occurs, protecting coastal areas from storms, supporting commercial and recreational fisheries, attracting millions of tourists, and providing a vast array of recreational opportunities.

As a reflection of the importance of South Florida coastal and nearshore habitats, the study area includes 60 sites of special concern, including State and National parks, aquatic preserves, wildlife refuges, and marine and estuarine sanctuaries (see **Chapter 11** for a complete listing). Prominent among these are Everglades National Park, Fort Jefferson National Monument, and the Key Largo and Looe Key National Marine Sanctuaries. In addition, the entire Florida Keys has been designated by the State as Outstanding Florida Waters and as an Area of Critical State Concern.

South Florida's coastal and nearshore habitats are subject to damage and stress by natural events such as hurricanes and cold fronts, as well as human activities associated with development in the Florida Keys. The Reef Tract exists at the northern threshold for reef development, and it is threatened by sediment influx and nutrient enrichment resulting from coastal development. Most mangroves within the study area grow under less-than-optimum conditions and can be classified as stressed. Coastal urbanization threatens seagrass and coral reef habitats by removing terrestrial vegetation and mangroves, which act as filters that absorb nutrient- and sediment-laden runoff. Occasional freshwater releases from canals into Florida Bay can result in severe damage to seagrass communities. Recent events such as the massive seagrass die-off in Florida

Bay and coral bleaching in the Reef Tract illustrate the fact that the continued health of these communities cannot be taken for granted. Any new human activity that might affect these communities must be evaluated against this background.

Regional Distribution of Coastal and Nearshore Communities

This chapter focuses on mangrove forests, coral reefs, and seagrass beds. **Figure 4.1** shows the general distribution of these communities within the study area.

Mangrove Forests

Mangrove forests once covered almost the entire coastline of South Florida, but coastal development has greatly reduced their abundance. Extensive mangrove stands still exist within the study area from Cape Romano southward around Cape Sable and across the northern shore of Florida Bay. Much of this coastline lies within Everglades National Park, and the mangrove forests there are among the most extensive stands remaining in Florida. Mangroves also cover many of the low islands and sand spits in Florida Bay. Although coastal development has reduced their abundance in the Florida Keys, there are still some extensive mangrove areas there. The Marquesas Keys, west of Key West, are completely mangrove-covered, and mangroves cover several of the low islands in the Dry Tortugas complex.

Coral Reefs

Three types of coral communities exist within the study area: (1) bank reefs, (2) patch reefs, and (3) live bottom areas.

Bank reefs occur along the outer edge of the Florida Reef Tract on the Atlantic side of the Florida Keys. Carysfort Reef and Molasses Reef off Key Largo and Looe Key Reef off Big Pine Key are good examples of outer or bank reef-type development in the Florida Keys. The Florida Reef Tract is more or less continuous from Fowey Rocks to the Marquesas Keys (**Figure 4.1**), but reef development is more pronounced off the Upper and Lower Keys. In the Middle Keys area, turbid water flowing in the numerous, wide channels connecting Florida Bay and the Atlantic retards reef development.

Behind the bank reefs, extensive patch reef communities have developed. Margot Fish Shoal off Elliott Key and Mosquito Banks off Key Largo are well-known patch reefs located between the Keys and the bank reefs. Patch reefs occur on the Gulf side (northern side) of the Lower Florida Keys as well, but their development in these areas is never as extensive as that on the Atlantic side.

The Dry Tortugas Bank (Fort Jefferson National Monument area) is a complex of reefs and sedimentary deposits. Bank, reef-type communities exist along the outer edge, whereas patch reefs are characteristic of the inner, or lagoon area.

Areas of low-relief hard bottom, exposed or covered by a thin sand veneer, are widely distributed in the study area. These hard bottom areas, often referred to as "live bottom," are colonized by a variety of reef biota, such as stony corals, octocorals, and sponges. The Southwest Florida shelf north of the Florida Keys is a complex mosaic of hard bottom and soft bottom habitats. Essentially, live bottom may be present at any specific location within the area indicated as "potential live bottom habitat" in **Figure 4.1**. Live bottom communities are discussed briefly in the Coral Reefs section of this chapter, and in more detail in **Chapter 5**.

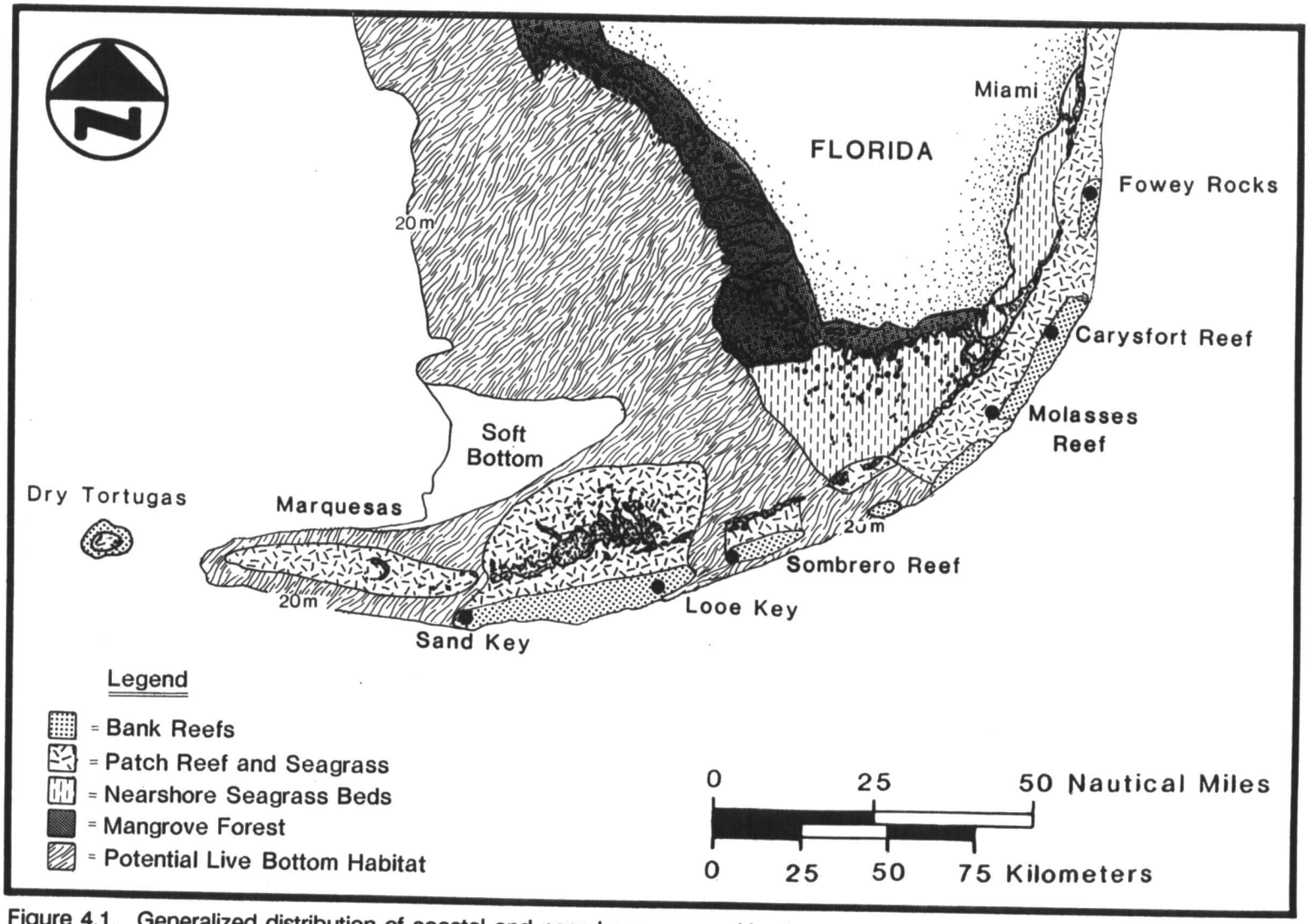


Figure 4.1. Generalized distribution of coastal and nearshore communities in and near the study area.

Seagrass Beds

Extensive freshwater drainage and turbidity entering the Gulf of Mexico through drainage systems of the Ten Thousand Islands and eastern Everglades (Shark River Slough) have prevented the development of extensive, nearshore, seagrass beds between Cape Romano and Cape Sable. However, south and east of Cape Sable, nearshore, seagrass-bed development is extensive. Florida Bay, a shallow, triangular lagoon/bay of approximately 1,500 km^2, is almost completely carpeted with seagrass and macroalgal communities. Major seagrass beds also occur on the Atlantic side of the Florida Keys shoreward of the outer barrier reefs. Nearshore seagrass beds occur throughout the Florida Keys, in and around the Marquesas Keys, and across the top of the Dry Tortugas Bank at Fort Jefferson National Monument.

Interrelationships among Coastal and Nearshore Communities

Although the major coastal and nearshore marine communities of South Florida are treated separately in this chapter, these communities are closely interrelated. Energy, chemical constituents, and fish and motile invertebrate species are exchanged between the coral reef, mangrove, and seagrass communities. Coral reefs provide shelter for organisms, such as fish and lobsters, that hunt at night in the seagrass beds. Mangroves and seagrass beds intercept nutrients and sediments entering coastal waters from terrestrial sources, thus helping to maintain the clear water needed for reef development. With their more plentiful supplies of nutrients, mangrove and seagrass communities also provide nursery areas for juveniles of many reef fish and invertebrates. Bank reefs form barriers at the oceanic margins, creating sheltered lagoons behind them where seagrass beds develop.

MANGROVE FORESTS

Samuel C. Snedaker

Mangrove Species

"True" Mangroves and Mangrove Associates

Mangroves are woody, arborescent, halophytic spermatophytes that are adapted to saline anaerobic sediments and commonly found along protected intertidal shorelines at tropical and subtropical latitudes. Chapman (1976) recognized a worldwide flora of about 55 species distributed among 16 genera in 11 families (see Barth 1982 for synonyms of the mangroves and mangrove associates). The mangrove flora of the Western Hemisphere is restricted to nine species distributed among five genera: *Avicennia bicolor*, *A. germinans*, *A. shaueriana*, *Conocarpus erectus*, *Laguncularia racemosa*, *Pelliciera racemosa*, *Rhizophora harrisonii*, *R. mangle*, and *R. racemosa*.

Although there are many mangrove species in the world, only a few qualify as "strict or true mangroves" for reasons discussed by Snedaker and Lahmann (1988). General criteria for distinguishing true mangroves have been outlined by Tomlinson (1986). The strict or true mangroves (1) exhibit complete fidelity to the mangrove environment, (2) comprise a major structural component of the mangrove community and have the ability to form pure stands, (3) possess specialized morphological and physiological adaptations relating to gas exchange, reproduction and osmotic control, and (4) are taxonomically isolated from their terrestrial, or glycophytic, relatives. Based on Tomlinson's criteria, there are three true mangrove species in the State of Florida: the red mangrove *R. mangle* (Rhizophoraceae), the black mangrove *A. germinans* (Avicenniaceae), and the white mangrove *L. racemosa* (Combretaceae). In this regard, there is only one recognized mangrove associate (*Conocarpus erectus* L., Combretaceae) in Florida, although there are a number of tree species, mainly exotics (e.g., Australian

pine *Casuarina equisetifolia* and Brazilian pepper *Schinus terebinthifolius*), that can invade and dominate disturbed or altered portions of the mangrove environment.

In addition to the tree flora, there is a relatively large variety of other vascular plants such as epiphytes (e.g., bromeliads, orchids), succulent herbs (e.g., glassworts, saltworts), and members of the Graminae (e.g., *Distichlis* sp., *Juncus* sp.) that occur in association with the mangrove community under certain specific conditions. For example, the halophytic herb flora requires relatively high ambient light exposure and infrequent tidal inundation. These ecological requirements tend to limit these halophytic species to ecotones, inland fringes of the mangrove community, and non-mangrove saline flats. However, it should be noted that the mixes of species also form discrete communities that contribute collectively to the overall landscape mosaic of the various kinds of tidally-influenced habitats. In this regard, they are integral components of coastal wetlands.

Morphological and Physiological Adaptations

Mangroves exhibit a number of specialized morphological-physiological adaptations that facilitate their existence in an environment that is too harsh or demanding for the vast majority of the world's higher plant flora (**Figure 4.2**). The principal adaptations relate to gas exchange, salinity tolerance, reproduction, and metabolic energy budgeting.

Gas Exchange. The natural exchanges of gases into (e.g., uptake of oxygen) and out of (e.g., releases of carbon dioxide, methane, hydrogen sulfide, etc.) the rhizosphere are frequently limited naturally by a low sediment permeability, high water table, and regular tidal inundation. These same factors also create a sediment environment within the rhizosphere that can be acidic, hypersaline, and strongly anaerobic, or reducing--conditions that are presumed to exact a metabolic cost on mangroves existing in that habitat. Mangrove survival is thus dependent on a number of adaptations pertaining to gas exchange between the rhizosphere and the overlying surface water or atmosphere.

Mangrove prop roots and pneumatophores, and their surface lenticels, represent a set of structural adaptations that facilitate uptake of oxygen for root respiration, and the corresponding release of the respiratory gas carbon dioxide. In this regard, it is interesting to note that *L. racemosa* does not normally develop aerial roots or a conspicuous abundance of lenticels except when growing on strongly reducing, anaerobic sediments. Field observations of this species suggest that the absolute density of small pneumatophores and large lenticels may be proportional to the reducing strength of the anaerobic sediment. Collectively, the functional importance of gas exchange structures is demonstrated whenever mangroves are subjected to sustained periods of higher-than-normal water levels. In such situations, gas exchange stops and the flooded mangroves enter a phase of respiratory distress which can lead to rapid mortality (Breen and Hill 1969; Vazquez 1983; Jimenez et al. 1985a,b). As discussed by these authors, the ultimate cause of mortality is the cessation of gas exchange.

Salinity Tolerance. Mangroves exhibit a number of physiological and structural adaptations that allow survival in saline environments. In general, these serve to prevent excess uptake of salt while enabling uptake of fresh water and nutrients. The major adaptations are of two broad types: salt exclusion and salt excretion. Salt exclusion may be accomplished by the non-metabolic ultrafiltration of seawater, and the passive accumulation of sodium chloride in xylem sap (Scholander 1968), and/or by the metabolically-driven accumulation of organic solutes (e.g., proline and mannitol) within the plant (Bernstein 1961; Pannier and Pannier 1977; Mizrachi et al. 1980; Stewart and Hanson 1980; Popp and Polania n.d.). Salt excretion occurs directly through specialized salt glands on leaves, and by salt entrainment in transpired water, and its subsequent release on leaf surfaces (Scholander 1968; Chapman 1976). Some authors have

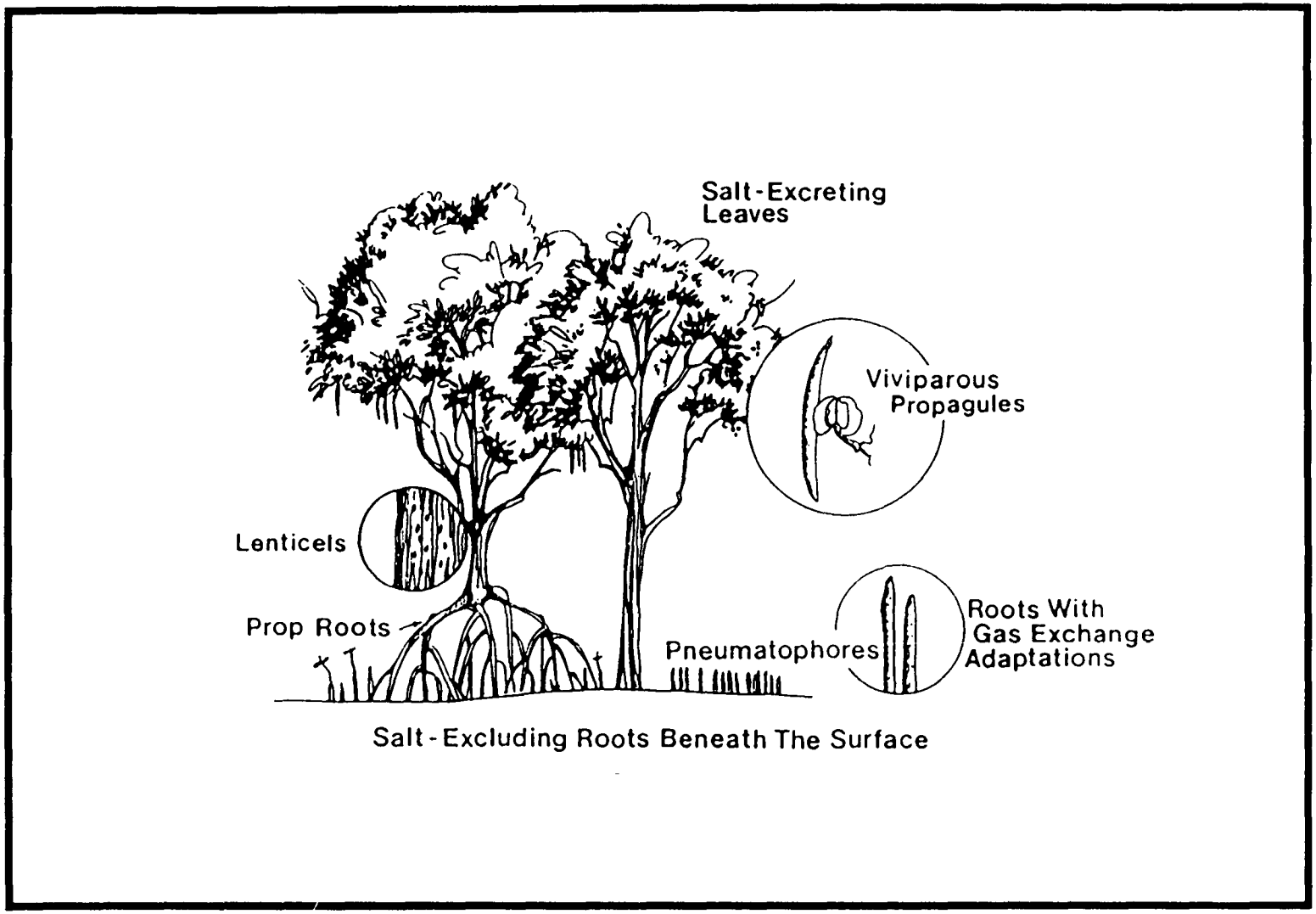


Figure 4.2. Examples of morphological adaptations in mangroves that permit their existence on anaerobic saline and saturated sediments in tropical and subtropical intertidal environments (From: Snedaker and Getter 1985).

proposed that internal salt concentrations are balanced by salt accumulation and its removal in germinating propagules (Genkel 1963) and senescent leaves. Whereas internal salt balances can also be affected by other phenomena such as salt dilution through increasing succulence (Nobel 1980), interconversion of non-soluble starch and soluble sugar (Kluge 1976), and neutralization of salt toxicity by calcium (Dost 1973), these alternative compensating mechanisms have not been demonstrated in mangroves.

Reproduction. Many mangrove species are viviparous in that seeds complete the germination phase while still attached to the mother tree (Chapman 1976), such as occurs in *R. mangle* and *A. germinans*. Germinating propagules also tend to accumulate large reserves of endosperm that can be metabolized at a later time (and thus are not forced to rely wholly on photosynthesis). An adaptive value of this fruiting strategy is that the seeds are in effect mature seedlings which can survive for extended periods prior to becoming established. As a result, viable seedlings can be widely dispersed by tides and currents while metabolizing the energy reserves stored in the endosperm. In contrast, the smaller and more numerous fruits of *L. racemosa* germinate following separation from the mother tree. The timing of the annual seed crop coincides with the seasonal period of high water and low salinity, generally in late summer and early fall in Florida. It can be argued that this phenological pattern is an evolved characteristic which serves to maximize both the dispersal of progeny and their establishment.

Energy Budgeting. Presumably because of the continuous respiratory demands imposed by the intertidal environment, true mangroves are ubiquitously evergreen (Snedaker and Lahmann 1988) and exhibit a continuing pattern of leafing and shedding. This characteristic among mangroves allows continuous photosynthesis to support the normal metabolic processes, as well as to provide metabolic energy for stress compensation and maintenance of the specialized adaptations. On an annual time scale, maximum leafing and increases in total leaf area occur during the spring period of warming and the initiation of summer rains. Coincident with development of the maximum complement of leaves, propagule germination is initiated and continues through summer; the propagule and seed crops mature in late summer. Propagule and seed fall, and the shedding of senescent leaves peak in September-October just prior to the winter period of reduced metabolic activity in the parent trees.

Adaptations and Environmental Stresses: Selected Examples

Because of the suite of specialized adaptations that enable mangroves to thrive in an otherwise harsh environment, environmental stresses that affect them either directly or indirectly have the ability to induce rapid mortality. In this regard, mangroves are particularly sensitive to any external stress which stops or limits rhizosphere gas exchange, as for example by sustained still water flooding (Lahmann 1988). Similarly, acute sedimentation that completely covers the substrate surface has the same effect, even though the above-ground gas exchange structures may remain relatively free of sediment coating. This phenomenon possibly indicates that a significant portion of the gas flux may occur through diffusion and advection at the sediment surface. To date, however, no one has attempted to measure the partition of gas exchange across the sediment surface versus that which occurs through the lenticels and bark.

Detrimental changes in mangrove vegetation also occur as a result of alterations within the rhizosphere when natural (Cintron et al. 1978) or man-made changes lead to hypersalinization, for example, by the cessation of tidal activity or by drainage. Although mangroves can survive short periods of hypersalinity, sustained episodes can lead to mortality. It is interesting to note that Scholander (1968) suggested that the upper salinity tolerance limit in *Rhizophora* is around 90 ppt, which is within the range in which calcium carbonate ($CaCO_3$) precipitates. Because $CaCO_3$ is a strong pH buffer, its precipitation and loss from solution allows the pH to drop in proportion to the strength of acids that may be present. Thus, the exact cause of mangrove metabolic

failure at 90 ppt and higher is open to question; it could be either a failure of the salt exclusion or salt compensation mechanisms, or a change in the membrane structure or root physiology as a result of a rapid drop in pH.

With regard to pH, it is important to note that mangrove sediments typically exhibit low pH. Therefore, the absolute pH value may be of lesser importance than the magnitude and rate at which it changes as a result of external forces. For example, drainage and subsequent oxidation of sediments with high concentrations of pyrite ($FeSO_4$) result in formation of sulfuric acid (H_2SO_4), which leads to a large and rapid drop in pH (Dost 1973). This, however, is not a potential problem in South Florida because carbonate sediments have extremely low concentrations of reduced iron compounds.

Mangrove Growth Forms

There is significant morphological variation in growth forms of individuals of each species of true mangroves. In the field, these forms may be recognized as normal, stunted, and dwarf. Although normal mangroves exhibit a variety of height and growth form patterns, they are recognized by an excurrent architecture including a dominant terminal lead shoot. In contrast, stunted mangroves tend to be abnormally short with excessive branching indicative of early periods of structural damage or dieback. Although stunting can be induced from a variety of stress conditions, stunted mangroves are most common at the northern latitudinal limits along the Florida coastlines where they are subjected to cold temperatures. Stresses such as frosts and freezes cause varying degrees of top-dying, and patchy to extensive areas of mortality (Macnae 1966; Lot-Helgueras et al. 1975; Lugo and Patterson-Zucca 1977).

Non-lethal cold temperatures tend to kill exposed terminal shoots and highest branches, but leave the lower branches, trunk, and root system unaffected. Presumably this is due to the latent heat capacity of sediment and water. Gill and Tomlinson (1971) argued that the mortality threshold in *R. mangle* is defined by whether or not the short-lived (two to three years) reserve meristem is deactivated. That is, a freeze which kills the last two to three years of woody growth (possessing the limited reserve meristem) as well as the apical meristems presumably renders the tree unable to recover. Both *L. racemosa* and *A. germinans*, however, have extensive regions of reserve or secondary meristem, and thus can recover from damaging frosts and freezes. However, because *A. germinans* seems to be, in general, the more cold tolerant of the Florida mangroves, it is the single species whose range extends into temperate regions around the Gulf coast.

If mortality does not occur during severe stress events (e.g., a freeze or a period of intense desiccation), there is renewed growth in the following growing season, which results in eventual appearance of terminal lead shoots. Also, if suitable growing conditions persist, a normal (i.e., excurrent) tree form develops. Repeated damaging stress events, however, re-initiate the cycle of die-back and regrowth, but the recovered tree reassumes an excurrent growth form and eventually develops a dominant trunk. Thus, stunted mangroves can and do occur over a range of height classes, whereas dwarf forms rarely exceed 2 m.

Although both dwarfing and stunting are believed to be stress-induced, dwarfing seems to be caused by the presence of persistent stresses which affect the rhizosphere. Although there is no evidence that dwarf mangroves represent a distinct genotype, it is recognized that environmentally induced dwarfism has an underlying genetic basis and is probably triggered by induced physiological changes. For example, nitrogen metabolism experiments on *R. mangle* indicate that as salinity increases, changes take place in amino acid and protein synthesis, affecting the organic solute pool (Mizrachi et al. 1980). Presumably, the synthesis of a large soluble amino acid pool to maintain an internal

osmotic equilibrium with the external environment could mitigate against plant growth in the context of competing nitrogen pathways. In this regard, evidence concerning whether or not salinity-induced changes in nitrogen metabolism is reversible, as opposed to being a permanent effect, is open to debate (cf. Kylin and Quatrano 1975; Kluge 1976).

In this latter regard, it is pertinent to note that beginning in the early 1900s, the "ditching" of mangroves and marshes throughout Florida was a common mosquito control practice used to eliminate mosquito breeding habitats through an increased frequency of tidal water turnover (Lahmann 1988). In areas of both stunted and dwarf mangroves, communities of tall, normally-formed (i.e., excurrent) mangroves eventually developed along the tidally-inundated ditches. Whereas this is good evidence of the positive response of mangroves to "improved" site conditions in dwarf (and stunted) mangrove habitats, there is no evidence that suggests whether or not the excurrent forms developed directly from the previously existing dwarf individuals or from newly established propagules from either dwarf or non-dwarf parents.

Dwarf Mangrove Characteristics

Dwarf and stunted mangroves are common throughout the Southeast Florida coastal region and the Florida Keys, with the largest single area occurring in southeastern Dade County. Although all three of the Florida mangrove species are present, *R. mangle* tends to be the dominant species, forming a discrete and relatively homogenous community that extends several kilometers inland. Within the Florida Keys, dwarf *R. mangle* are common within and around the infrequently inundated salt ponds, particularly in the Lower Keys. Because this is the dominant growth form within the study area, the *R. mangle* dwarf is described to distinguish it from the stunted and normal, or tall, forms of the species. Some of the characteristics that morphologically and ecologically distinguish dwarf mangroves from the normal and stunted forms in the study area include the following:

- The mean maximum height of mature dwarf mangroves is 1 m or less (Teas 1974; Pool et al. 1977), with occasional emergents in excess of 1 m, but seldom over 1.5 m.

- The growth form of dwarf *R. mangle* is decurrent and all branches are orthotropic. In contrast, non-dwarf growth forms are uniformly excurrent, with significant plagiotropic branching (Tomlinson 1978).

- Dwarf *R. mangle* in Southeast Florida can live for an extended period of time; they are mature plants. Minimum ages of the presumably oldest trees have been estimated at 40 to 60 years (Snedaker and Stanford unpubl. data) and older (Teas 1974).

- Dwarf *R. mangle* generally retain leaves longer (15 to 17 months) than do non-dwarf forms (9 to 14 months) (Pool et al. 1975; Snedaker and Brown unpubl. data).

- Total above-ground standing stock biomass of dwarf mangrove communities is one to two orders of magnitude lower than communities of non-dwarf mangroves (Lugo and Snedaker 1974). This is attributable to the small stature and low spatial density of dwarf mangroves.

- Dwarf mangroves exhibit significantly reduced rates of gross and net primary productivity compared to non-dwarf mangroves, but are similar in patterns of total 24-h respiration (Lugo and Snedaker 1974).

- In spite of low biomass and low net primary productivity, litter production rates in dwarf *R. mangle* are of the same order of magnitude as for non-dwarf forms (Pool et al. 1975; Snedaker and Brown 1982).

- Sizes of mature sun leaves of dwarf *R. mangle* are significantly smaller than for *R. mangle* growing under more optimum conditions (Lugo et al. 1981). Dwarf *R. mangle* leaves tend to be oblate in shape compared to a more strongly lanceolate shape in non-dwarf individuals (Snedaker and Brown unpubl. data).

- Annual propagule crops in dwarf *R. mangle* have been estimated to average approximately 130 propagules per individual (Snedaker unpubl. data) compared with an estimated 300 propagules for non-dwarf individuals (Davis 1940).

- Dwarf *R. mangle* propagules tend to be smaller that those from non-dwarf populations; sizes are within the range reported for mangroves exposed to persistent heat stress from power plant effluents (Banus and Kolehmainen 1976). Banus and Kolehmainen reported a reduced propagule survivability, but equivalent information is not available for the small propagules of dwarf *R. mangle.*

- In Southeast Florida, dwarf *R. mangle* can survive dry season interstitial sediment salinities that occur in considerable excess of 90+ ppt, whereas the normal maximum range for non-dwarf forms in the same region is around 35 to 40 ppt (Snedaker and Stanford unpubl. data).

The Mangrove Environment in South Florida

The major mangrove complex in Florida occurs in the extreme southern region in Collier, Monroe, and Dade Counties. The regional pattern at this scale reveals the influence of freshwater runoff, which tends to be greatest in the south and southwest. Where salinity levels are moderated by a prolonged seasonal influx of freshwater runoff from the terrestrial landscape, mangroves tend to achieve their maximum size and structure. Pool et al. (1977) have shown that freshwater runoff and its entrained terrigenous nutrient load can account for most of the variation in mangrove forest structure and complexity within a region. The positive influence of freshwater and nutrient availability can be observed particularly in the western portions of the Everglades National Park and in the area of the Ten Thousand Islands where mangroves achieve greatest development in Florida. It should be noted however, that Florida is exposed to hurricanes which prevent the structural development of mangroves equivalent to that found in Caribbean mangrove forests outside of the hurricane belt (Lugo et al. 1975).

In the southeastern portion of the South Florida mangrove region, mainly in southeastern Dade County, the structural development of mangroves and mangrove communities is limited by the absence of significant freshwater and nutrient runoff. Egler (1952) has stated that the more coastal portions of the southeastern saline Everglades were changed from low salinity to high salinity environments by the construction of roads and railways, and land drainage, around the turn of this century. This area is presently dominated by broad expanses of dwarf mangroves interspersed with small islands of taller mangroves. These mangrove islands, or hammocks, were once dominated by glycophytic tree species which still occur in the hammocks and strands of the freshwater Everglades. Progressive reduction in freshwater runoff in the form of sheet flow, over the past several decades, has altered much of the vegetation complex of South and Southeast Florida, and is a topic of concern in the State of Florida's Surface Water Improvement and Management (SWIM) Plan (South Florida Water Management District 1988).

Mangrove Habitats

Mangrove Forest Types

Under presumed optimal conditions, mangroves form monospecific and mixed-species closed canopy forests which at maturity range from several meters to over 40 m in height (Golley et al. 1975; Pool et al. 1977); a well-developed forest structure is the most ubiquitous physiognomic expression in most mangrove-dominated regions. Under less-than-optimum conditions, there is an extraordinarily large variation in mangrove species composition and structural development. The major variations have been classified in terms of monospecific zonation along well-defined environmental gradients (cf. Snedaker 1982) and as structural forest types (**Table 4.1, Figure 4.3**) that are correlated with broad differences in hydrology and salinity (Lugo and Snedaker 1974).

The principal mangroves forest types have been shown empirically to be significantly related to characteristic patterns of tidal inundation and exposure to freshwater runoff (cf. Pool et al. 1977; Snedaker and Brown 1981; Twilley et al. 1986). Implicit in the characterization is the relationship between these hydrological factors and such auto-correlates as interstitial sediment salinity, terrigenous nutrient availability, redox potential, and metabolic waste (including mineral sulfides) removal by periodic flushing (Lugo and Snedaker 1974). Within conservative limits, the mangrove forest types are commonly recognized as quasi-predictable expressions of mangrove forest responses to the broad characteristics of the environments in which they occur.

Within the Southeast Florida region, including the Florida Keys, there are five recognizable forest types based on the classification scheme of Lugo and Snedaker (1974), and summarized in Snedaker (1989). These are the mangrove fringe, overwash, basin, dwarf, and hammock forest types. Significant areas of the riverine forest type are not present due to the relative absence of freshwater rivers and their floodplains. The hammock forest type (not shown in **Figure 4.3**) is restricted to extreme southeastern Dade County. The mangrove fringe and overwash forests are similar in that these types occur on shorelines exposed to open water, are inundated on all high tides, and tend to be dominated by *R. mangle*. The principal difference is that in the fringe forest, incoming and outgoing tides follow the same directional patterns, whereas in the overwash forest, high-tide waters pass completely through the forest community. Basin forests, in contrast, are located inland from the shoreline, sometimes at slightly higher elevations, and are inundated only by the highest of high tides. In these less frequently inundated settings, there is a tendency toward a persistently elevated interstitial or pore water salinity, a stronger reducing environment within the anaerobic rhizosphere, and an *in situ* accumulation of leaf litter and organic debris. The structure and species composition of the basin forest are highly variable and can range from a fully-stocked mixed-species forest to a relatively open forest dominated by *A. germinans*. Within the Florida Keys, basin forest vegetation is frequently associated with salt ponds (infrequently inundated, hypersaline as the result of high evaporation) and dwarf and stunted trees. The principal characteristics of this vegetation pattern are similar to those described for mangrove island complexes in the arid parts of the Caribbean (Cintron et al. 1978).

The large expanse of dwarf mangrove vegetation in Southeast Florida occurs interspersed with isolated mangrove forest hammocks and is bordered by a frequently inundated fringe forest. The more inland area of dwarf mangrove vegetation is significantly inundated only during late summer and early fall periods of high sea level and high groundwater tables. During winter and spring, the areas become dessicated and saline which presumably contributes to the dwarf nature of the vegetation. Mangrove forest hammocks within the dwarf vegetation exist over deep blocks of organic peat (Zieman 1972). Organic peat probably contributes to the structural development

Table 4.1. Mangrove forest-type characteristics and associated functions based on the classification system of Lugo and Snedaker (1974) (From: Snedaker 1989). Data and comments pertain primarily to Western Hemisphere mangrove environments.

Forest Type	Topographic Type	Inundation Pattern	Soil Salinity Range	Forest Height* (m)	Mean Stand Diameter* (cm)†	Complexity Index*§	Litter Production¶ Mg/ha/yr	Detrital Export Form
OVERWASH	Low islands and small peninsulas	Completely overwashed on all high tides	Brackish to seawater (20-35 ppt)	6.37 + 0.92	11.12	13.17 + 6.70 2.17 + 1.78	9.00 + 0.72**	Particulate (continuous)
FRINGE	Shorelines with steep elevation gradient	Inundated and flushed by all high tides	Brackish to seawater (20-35 ppt)	7.65 + 0.94	8.31	26.44 + 12.50 1.54 + 0.84	9.00 + 0.72**	Particulate (continuous)
RIVERINE	Floodplains along river drainages	Inundated by most high tides, flooded during wet season	Moderate to low salinity (1-25 ppt)	12.64 + 1.43	19.37	38.77 + 11.62 22.76 + 9.91	12.98 + 1.01	Particulate and some dissolved (pulsed)
BASIN	Partially impounded depressions	Inundated by few high tides during dry season, and most high tides during wet season	Brackish to moderately hypersaline (20-70 ppt)	12.14 + 1.29	10.53	18.41 + 3.04 4.09 + 2.05	6.61 + 0.70	Mostly dissolved (pulsed)
DWARF	Topographic flats above mean high water	Tidally inundated only during wet season; dry for most of year	Brackish to highly hypersaline (45-90+ ppt)	1.0‡‡	1.75‡‡	1.5‡‡ 0.0§§	1.86 + 0.55	Mostly dissolved (highly pulsed)

* Data from Pool et al. 1977; data expressed as mean and standard error.
† Mean diameter of all trees >2.5 cm computed according to Cintron and Schaeffer-Novelli (1984).
§ Complexity indices computed respectively for trees with diameters >2.5 cm <10 cm and >10 cm.
¶ Data from Twilley et al. 1986; data expressed as mean and standard error.
** Litterfall data for overwash and fringe forests are not significantly different and have been grouped into one estimate.
‡‡ Single value.
§§ No trees with diameters >10 cm.

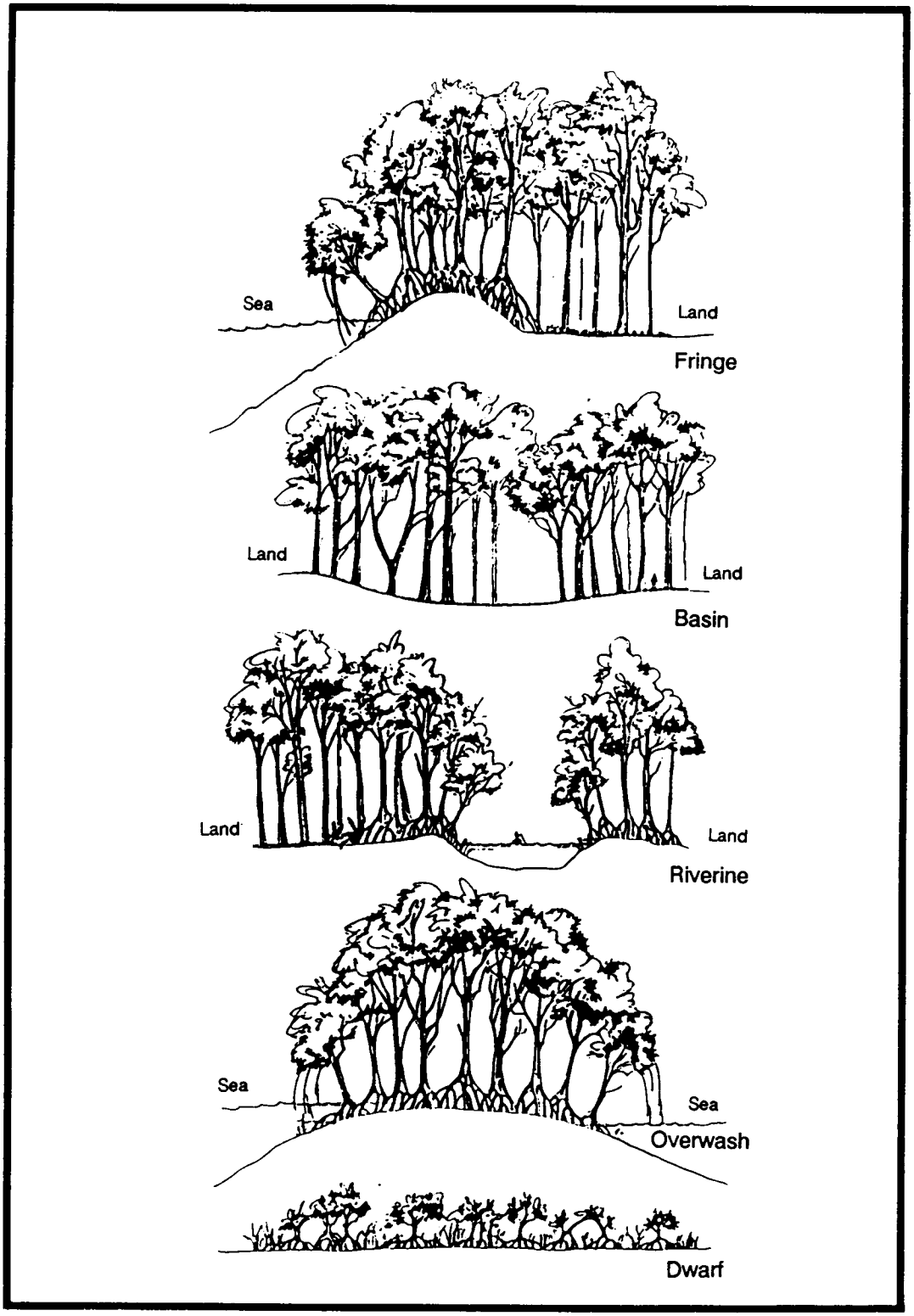


Figure 4.3. Structural and functional variations among mangrove forest types (From: Snedaker and Getter 1985). The variations are controlled mainly by differences in land elevation, freshwater runoff, and pattern of tidal inundation.

of the hammock forest by providing a source of nutrients (through *in situ* remineralization of organic matter), and improved water relations as a result of the high moisture-holding capacity of the peat block. Because these dwarf forest areas are only seasonally inundated and flushed, much of the mangrove detritus decomposes *in situ* and then is flushed out in the form of fine particulates and dissolved organic carbon to Card Sound, Little Card Sound, Barnes Sound, and other smaller sounds and bays along the coast during late summer and early fall. Based on the developing scientific literature on dissolved organic carbon in marine systems, Snedaker (1989) suggested that this seasonal flush results in an ephemeral food web dominated by microheterotrophs.

Mangrove Productivity

Mangrove forests are widely recognized as highly productive, tropical, coastal ecosystems which are associated with the high secondary productivity of contiguous shallow waters. Recognition of the high productivity of mangrove forests seems to have its origin in the 19th century in Asia where colonial foresters implemented sustained-yield management plans in such countries as Bangladesh (formerly, Bengal and East Pakistan) and Malaysia for the purpose of harvesting mangrove forests for a variety of wood products, including paper pulp (cf. Watson 1928; Curtis 1933; Khan 1966). In general, these early management plans represented the first attempts to estimate productivity, although the emphasis was on the production, or yield, of wood and wood products. In contrast, in the Western Hemisphere, mangroves were considered to be little more than botanical curiosities that made land (Davis 1938, 1940), and mangrove environments were both officially and subjectively considered to be unsuitable for economic use (Gallatin et al. 1958). In this regard, the large areas of dwarf and stunted forests in Southeast Florida were once specifically considered to be wastelands (Humm 1969).

Golley et al. (1962) conducted the first empirical study that revealed the productive nature of mangroves, particularly with respect to the production of leaf litter, or detritus. However, it was not until the studies of Odum (1969, 1971) and Heald (1971) that the magnitude of production was established and linked directly to the estuarine food web. Their work is credited with establishing the basis for the conservation of intertidal mangrove-dominated wetlands because of the role of leaf litter production and decomposition in the maintenance of nearshore fisheries (see also Fell et al. 1975; Fell and Master 1980). The role of mangroves in secondary production of fisheries has been validated for penaeid shrimp in Indonesia (Martosubroto and Naamin 1977) and throughout the world (Turner 1977). Although there is no longer any major dispute concerning the relatively high productivity of mangroves, it is only recently that good empirical and comparative data have been obtained. This has subsequently led to extensive research on the environmental controls that govern rates of productivity in specific environments.

Environmental Control of Mangrove Productivity

Much early work on mangroves (see reviews by Walsh 1974; Lugo and Snedaker 1974; Chapman 1976) focused on descriptive surveys of mangrove species and habitats. In general, these surveys revealed that mangrove establishment and perpetuation are largely independent of the substrate type; mangroves occur, for example, on clay, silt, sand, gravel, shell, coral, and carbonate muds in many types of depositional settings (see also Thom 1982). Mangroves also grow over a wide range of pH and Eh (a measure of reduction/oxidation potential), and interstitial salinities that range from >0 to 90+ ppt over the course of a year. Although mangroves can adapt to a wide variation in microhabitat conditions, they cannot establish and survive along exposed coastlines that experience strong wave action. Although mangroves, as a group, can occupy and

dominate a large variety of subtropical coastal habitats, productivity rates tend to be site-specific or region-specific phenomena, largely controlled by the availability of fresh water (e.g., as a salt-dilution factor) and a continuing supply of terrigenous nutrients. In a physiological context, lowered interstitial salinities lead to reduced respiration, and abundant nutrients tend to stimulate gross primary productivity as suggested above. The result is that net primary productivity is increased.

Pool et al. (1977) made a multiple-site comparison of the structure of mangrove forests in Florida, Mexico, Puerto Rico, and Costa Rica in relation to availability of fresh water. The results showed that mangrove forest development was greatest (i.e., higher species diversity, taller forest height, larger forest basal area) in areas of high precipitation and/or freshwater runoff. Implicit in the aspect of freshwater runoff that enters the intertidal zone is the delivery of primary plant nutrients that are derived from terrigenous sources. This basic relationship has been confirmed elsewhere, for example, in Ecuador (Cintron and Schaeffer-Novelli 1981), India (Blasco 1977), Gambia (Blasco 1983), and Pakistan (Snedaker 1984). In many of these countries, reductions in freshwater inflow due to dams and river diversion projects have been associated with decreasing productivity and mangrove mortality.

The empirical relationship between interstitial sediment salinity and mangrove productivity has been fairly well documented. Carter et al. (1973) and Hicks and Burns (1975) presented data and discussed the correlation between interstitial salinity (specifically pore water chlorinity) and respiration, and the general effect on metabolism. In addition to the direct influence that salinity has on respiration and therefore on carbon metabolism, the overall effect is expressed in the spatial distribution of the mangrove species relative to competition and zonation (Lugo et al. 1975; Snedaker 1982). This is an important relationship because any factor that alters the spatial and temporal pattern of interstitial salinity will induce a corresponding change in both species dominance and the spatial organization of individuals in mixed-species communities.

Rates of Primary Productivity

Primary productivity can be divided into two basic parts: gross primary productivity (GPP) and net primary productivity (NPP), in which the latter is calculated by taking the unit-period value of GPP and subtracting the unit-period value of respiration (R) (Newbould 1967; see also Whittaker et al. 1975). In essence, GPP represents the total sum of carbon assimilated and fixed during photosynthesis whereas NPP represents that residual fraction of the GPP which remains after all metabolic maintenance costs (R) have been subtracted. The results are typically expressed as grams carbon fixed per square meter per unit time (i.e., g $C/m^2/d$).

Snedaker and Brown (1982) summarized the available data on GPP, NPP and R, and the published rates of mangrove litter production. These data show that mangrove communities can exhibit very high rates of primary productivity (e.g., GPP = 13.9 g $C/m^2/d$). More importantly, they reveal that the rates of productivity exhibit a relatively large spatial variation which reflects the variable characteristics of local environments. It should also be noted that GPP, NPP, and R are not intercorrelated with one another, due mainly to the fact that different environmental factors regulate the rates of GPP and R (see data in Lugo and Snedaker 1974; Snedaker and Brown 1982). For example, in a situation in which there is a simultaneous stimulation of GPP due to an abundance of inorganic nutrients and an increase in R due to an elevated soil salinity, the positive influence tends to balance the negative. In a similar context, the accumulation of standing stock biomass is a function of primary productivity, specifically NPP, although no satisfactory empirical correlation can be demonstrated between these two parameters (see Lugo and Snedaker 1974; Clough and Attiwill 1982; Snedaker and Brown 1982).

This very basic metabolic relationship between productivity and respiration has practical implications that have not been fully evaluated with respect to mitigating severe pollution in mangrove areas. For example, Snedaker (1984) has observed that mangroves growing in heavily polluted Karachi Harbor (Pakistan) are remarkably healthy as a result of the sewage wastes (and accompanying fresh water) entering the harbor; the respiratory stress of pollution is offset by the stimulating effect of nutrients and reduced salinity. Research on the artificial fertilization of damaged mangroves is clearly indicated.

Litter Production

Litter production represents a variable fraction of NPP, specifically those organic tissues and structural components that do not become part of the permanent standing stock, but instead are shed in a somewhat predictable pattern (e.g., leaves, reproductive organs, bark, etc.). It is pertinent to note that in contrast to the relatively large variation in the rates of GPP and NPP (variation in excess of two orders of magnitude), the rates of litter production tend to be relatively uniform with a variation limited to one order of magnitude (Snedaker and Brown 1982). Published data for litter production indicate that the maximum range in mean values (grams dry-weight) is from a low of 0.6 to a high of 4.33 g dry wt/m^2/d (Bunt 1982; Snedaker and Brown 1982). The global average for litter production is close to, or in slight excess of, 2 g dry wt/m^2/d.

The relative uniformity among published rates of litter production indicates that there may be a carbon metabolism or an organic production strategy within mangrove species that serves to optimize production and maintenance of photosynthetic tissues (i.e., leaves) at the expense of the net accumulation of standing stock biomass in the form of woody structures (cf. Snedaker and Lahmann 1988). This means that litter production is, at best, only partially correlated with other parameters that define both organic production and accumulation of standing stock biomass (Lugo and Snedaker 1974; Snedaker and Brown 1981, 1982). Notwithstanding, some researchers (e.g., Teas 1974; Lahmann 1988) argue that litter production uniformly varies proportionately with primary productivity, which it may in any site-specific situation.

Detrital Flux and Marine Life

In comparison to the relatively large literature on South Florida mangroves as species and communities, and on ecosystem processes and functions, there is a paucity of reported research on the marine fauna associated with, and dependent on mangroves (e.g., Odum 1969, 1971; Snedaker and Lugo 1973; citations in Odum et al. 1982; Thayer et al. 1987). This is somewhat of a paradox in that the legal protection of mangroves is based wholly on the associated marine fauna, particularly the commercial and recreational fisheries, and incidently a number of rare and endangered species, including terrestrial species. The best synthesis to date (Odum et al. 1982) indicates that the distribution of the major faunal groups can be correlated with broad habitat types (i.e., tidal stream, estuarine bay, and oceanic bay) and diet preferences, and, for certain fish communities, with four of the mangrove forest types (basin, riverine, fringe, and overwash).

In addition to the biophysical habitat role of mangroves, this coastal vegetation complex contributes directly to the support of nearshore marine life through the production and export of organic matter, or detritus, in both particulate and dissolved forms. Detritus in the form of particulate organic matter (POM) results when whole mangrove leaves (and other small debris) are exported on outgoing tides and decompose in the nearshore waters. During the biological decomposition process, microorganisms colonize the POM and utilize the plant carbohydrates as an energy source. As a result,

the aggregate protein content of the POM increases to a higher nutritional level as a result of the increasing microbial biomass. Marine organisms which then consume the POM mainly remove and digest the microorganism colonies. The remains of the leaf particles then pass through in the feces and are eventually recolonized (Odum 1970). Because *R. mangle* produces most of the whole leaf detritus that is exported, this one species of mangrove is given greater legal protection than the other mangrove species (Snedaker 1989).

Dissolved organic matter (DOM) results from the leaching of soluble organic carbon from mangrove leaves and other plant surfaces, such as branches and bark, and from the decomposition/oxidation of reduced organic matter in sediments. In addition, *in situ* decomposition of detritus in infrequently inundated mangrove habitats (e.g., basin and dwarf forests) results in production of significant quantities of DOM and fine particulates which are exported only at times of high-water inundation. It is only relatively recently that reports have been written on the role of mangrove DOM in nearshore waters (Cooksey et al. 1975; Camilleri and Ribi 1986; Alongi 1987); based on these and other works, the postulated multiple roles of DOM in Southeast Florida nearshore waters has been summarized by Snedaker (1989). In this regard, it seems that DOM represents the largest single source of exported mangrove organic matter, mainly because the producing habitats cover a much larger area of Southeast Florida than those habitats (e.g., fringe and overwash forests) which export whole leaves (POM) on daily high tides. Also DOM is chemically richer and more diverse than POM which is primarily composed of carbohydrates.

Pollutant Fates and Effects

Introduction

Coastal water pollution is a generic problem particularly in sheltered intertidal areas. In this regard, Hayes and Gundlach (1979) consider tropical mangroves to be one of the most sensitive of all coastal ecosystem types. Pollution effects on mangroves are varied and include mortality, stunting, reduced seedling survival, morphological aberrations, developmental deformations, defoliation, and changes in rate and pattern of leaf litter production. However, in some highly polluted coastal areas (e.g., ports and harbors), mangroves frequently seem to be unaffected which may lead observers to suggest that mangroves are relatively resistant to pollution, or that the severity of the pollution is overstated. Such observations fail to take into account the fact that (1) the response may be both species and pollutant specific, (2) the effect may be severe on the cryptic components of the ecosystem such as the invertebrate infauna, and (3) certain pollutants (e.g., metals and organic chemicals) may be directly introduced into nearshore food webs via their incorporation and subsequent transport in leaf detritus. Although there is widespread interest in mangrove research and management, the number of pollution studies is extremely limited. For example, in Rollet's (1981) indexed bibliography on mangroves, there are only 12 citations indexed under the heading of "pollution" out of a total of 5,608 mangrove titles published through 1975.

Although there are a number of reported instances of mangrove mortality that can be attributed to both pollutants and a variety of other causes (Jimenez et al. 1985b), reports of sublethal effects have been mostly anecdotal in nature. In this regard, Snedaker and Brown prepared a list of observed "stress symptoms" in mangroves, some of which were incorporated earlier in a broad "mangrove stress index" (Getter et al. 1980) for use in an oil spill assessment. These sublethal stress symptoms are listed in **Table 4.2** as a general overview of the variety of observable responses that can be exhibited in mangroves and mangrove communities subjected to external stresses. Because many of these symptoms can be induced by natural stresses, studies incorporating "controls" are often necessary to relate specific causes with any observed effects.

Table 4.2. Stress symptoms in mangroves.

Aerial Root Structures
- Proliferation of undersized prop roots
- Twisting and curling of pneumatophores
- Presence of adventitious aerial roots
- Death of prop root tips
- Abnormal aerial branching of prop root tips
- Fissuring or peeling of periderm

Trunks and Branches
- Top-dying of uppermost and outermost sun branches
- Fissuring and cracking of bark
- Expanded and/or more numerous lenticels
- Shortened internode distances
- Cessation of terminal shoot growth
- Appearance of trunk sprouts from secondary meristem

Foliage and Canopy
- Reduced leaf number per branch
- Reduced leaf size, twisting or curling
- Increased variability in leaf size and shape
- Abscission of buds and immature leaves
- Altered leaf maturation sequence
- Spotty chlorosis or necrosis
- Change in leafing and shedding patterns
- Reduced leaf area index

Reproductive Structures
- Change in timing of flowering and fruit set
- Absent or grossly excessive flowering
- Deformed seeds and propagules
- Developmental failure of fruit
- Abortion of flowers or immature fruit

Regeneration
- Failure in geotropic orientation in propagules
- Failure of seeds and propagules to establish primary root system
- Failure to initiate primary branching
- Abnormal growth forms in established seedlings
- Chlorosis or necrosis of propagules

Effects of heavy metals and synthetic organic compounds are discussed below. Effects of oil spills are reviewed and discussed in **Chapter 15.**

Heavy Metals

Research on the fate and effects of heavy metals in the mangrove environment consists of several controlled laboratory experiments and a limited number of field surveys. In Florida, the laboratory research focused on metal uptake and accumulation experiments using young-of-the-year propagules and/or seedlings of two species of *Rhizophora* and one species of *Avicennia*. Walsh et al. (1979) experimented with Florida *R. mangle* seedlings, using the metals cadmium, lead, and mercury. In a similarly designed experiment in Malaysia, Thomas and Ong (1981) used seedlings of the Asian mangroves *R. mucronata* and *A. alba* exposed to treatments of lead and zinc. Lead and zinc were not significantly absorbed or translocated whereas cadmium and mercury were translocated to the hypocotyls and leaves, but were apparently detoxified. Neither group of researchers investigated the role of substrate chemistry and biological activity in the enhancement or reduction in the uptake of metals. For example, uptake can be enhanced by chelation with an organic ligand, by biologically-mediated methylation, or as the result of increased solubility as a chloride. Conversely, uptake can be inhibited for those metals that are sequestered as a sulfide or which are complexed with soil humates. In the latter example, sediment is only a temporary sink which can be reversed by changes in Eh, pH, and salinity--events which periodically take place in the mangrove environment (Lu and Chen 1977; Harbison 1984). Secondly, although the uptake phenomenon may not result in the manifestation of acute effects on mangroves, as illustrated by the Florida and Malaysian experimental research, it does demonstrate the biological concentration of metals in those tissues destined to enter detrital food webs (DeLaune et al. 1981). In any event, it is difficult to extrapolate the experimental findings to reproductively mature adult plants because developing seedlings are, in part, nourished by endosperm reserves whereas mature plants rely entirely on photosynthesis and the external environment for water and nutrients.

Various field surveys for metals in the mangrove environment have shown collectively that mangroves concentrate metals in foliar tissues at significant levels above background concentrations (Carter et al. 1973; Tripp and Harriss 1975; Snedaker and Stanford 1976; Peterson et al. 1979; Snedaker and Brown 1981; Thomas and Ong 1981; Harbison 1986). For example, Snedaker and Brown (1981) reported the following concentration factors for leaves of mature mangroves in Southeast Florida: chromium 5-6x, copper 1-2x, iron 2-3x, lead 4-5x, manganese 3-4x, nickel 4-5x, and zinc 1-2x. In this specific regard, Peterson et al. (1979) proposed the use of mangroves for biogeochemical prospecting for tin (and copper, iron, and zinc) because of the relatively high concentrations of those metals in the leaves of mangroves exposed to natural sources (e.g., surficial placer deposits).

These field results, partially corroborated by experimental work, indicate that mangroves are relatively tolerant to metal toxicity but may well be a significant transient source of metals in estuarine food webs. Specific resistance of mangroves to metal toxicity (Walsh et al. 1979) could be associated with one or more of the following phenomena: (1) detoxification within the plant by chelation in the cell wall (Antonovics et al. 1971), (2) the osmoregulatory ion-exclusion mechanism described in *Rhizophora* by Scholander et al. (1964) could effectively exclude metal ions, and (3) internal concentrations of metals could be regulated by excretion through the numerous salt glands found, for instance, in the leaves of *Avicennia* (Thomas and Ong 1981), thus preventing an internal buildup of toxic conditions.

Synthetic Organic Compounds

Research on the interaction, fate, and effects of synthetic organic compounds is even less conclusive than the work on metals, and has focused on biocides. Like the research on metals, the existing knowledge is based on several laboratory experiments using propagules and seedlings of *Rhizophora* and *Avicennia*, and on surveys in the mangrove environment. In addition, there is one major field experiment using herbicides, but results are in partial conflict with the laboratory studies. Research in this area is limited to investigations of two groups of biocides (herbicides and insecticides) and one polychlorinated biphenyl (PCB).

Mangrove sensitivity to herbicides was first investigated by Truman (1961) in Australia, using *Avicennia marina*, and 2,4-D and 2,4,5-T. Truman found *A. marina* to be highly sensitive to small concentrations of these auxin-type herbicides, a fact that was confirmed during the Vietnam War when large areas of mangroves were defoliated and killed (see Tschirley 1969; Orians and Pfeiffer 1970; National Academy of Sciences 1974). Subsequent research on herbicides grew out of the Vietnam experience.

Walsh et al. (1973) conducted a pot study using *R. mangle* seedlings (18.2 to 26.5 cm tall) treated with three concentrations of Dow Chemical Company Tordon 101R (similar to "Agent White" used in Vietnam) which is a mixture of 2,4-D and picloram. The experiments indicated that *R. mangle* seedlings were more sensitive (lower effects threshold) than other tropical tree species. More importantly, they showed that 2,4-D and picloram were translocated at all treatment levels as they were detected in roots, hypocotyls, stems, and leaves. Histological examinations showed corresponding cell wall breakdown in both roots and leaves.

Teas and Kelly (1975) conducted a field experiment in Southwest Florida in an area of mature, mixed-species, mangrove forest that was designated for clearing for a housing development. The treatment consisted of aerial spraying of Tordon 101 by helicopter. Teas and Kelly concluded that *L. racemosa* was the most sensitive of the three mangrove species; it exhibited 100% mortality. *R. mangle* exhibited a marginal sensitivity, and *A. germinans* proved to be relatively resistant. To a qualified extent, the work of Teas and Kelly conflicts with the works of Truman (1961) and Walsh et al. (1973) who showed *Avicennia* sp. and *R. mangle* to be relatively sensitive. No obvious

explanation is apparent other than that which might be associated with either the experimental technique, or the inability to make comparisons between seedlings and adult plants.

Research on other pesticides and PCBs is more limited and less conclusive about the overall effects in the total mangrove environment. Based on the detection of dieldrin and PCBs in *R. mangle* leaves in the U.S. Virgin Islands, and the insecticide DDD (dichloro-diphenyl-dichloro-ethane) in the roots, hypocotyls, stems, and leaves of *R. mangle* seedlings in Puerto Rico, Walsh et al. (1974) conducted controlled laboratory experiments to confirm those findings. Potted *R. mangle* seedlings were exposed to dieldrin, methoxychlor, mirex, and the PCB Arochlor 1242. It was found that each of these compounds could be taken up and translocated, as each was detected in the roots, hypocotyls, and leaves. Other surveys for pesticides in mangroves in Florida and Puerto Rico could not confirm the experimental work (Carter et al. 1973; Snedaker and Brown 1981). However, investigations were not made of microbial breakdown/decomposition in the sediment, or sequestering therein, or were projections made about the transport of these substances to the marine environment in the detrital flux.

Overall, the research on the synthetic organic compounds and related biocides suggests that mangroves can take up and accumulate synthetic organic substances, and that the effects are dose determined, species specific, size and age specific, and probably modified by prevailing environment conditions. For example, the herbicide 2,4-D can form complexes with proteins, especially via lysine, and could severely interfere with the salt resistance mechanisms in *R. mangle* (see Mizrachi et al. 1980). In sediment, 2,4-D tends to hydrolyze to form free acids, whereas in distilled water, esters remain unchanged. PCB uptake from soils is enhanced by ultraviolet radiation, and its presence in water tends to lead to dechlorination and the creation of lower molecular weight chlorinated hydrocarbons. No research has demonstrated these transformations in saline, reducing mangrove environments, and no work has been done to demonstrate whether or not mangroves can metabolize the newer pesticides. Metabolites tend to have a higher water solubility, and thus, their fate and effects would be expected to differ significantly from the parent compound.

Conclusions

Almost the entire undeveloped, non-beach shoreline of South Florida comprises a habitat for a landscape mosaic of mangrove forest types. The various types reflect natural differences in such forcing functions as volume and frequency of tidal inundation, degree of exposure to freshwater runoff, and site fertility (cf. Lugo and Snedaker 1974). In addition to mangroves being the dominant form of coastal wetland vegetation, research in South Florida in the early 1970s (summarized in Snedaker 1989) provided the basis for much of our knowledge about this marine forest type. In spite of the heavily documented importance of mangroves for nearshore fisheries, the total area of mangroves in South Florida has steadily declined since the early 1900s, primarily as the result of development. The destructive trend, however, has slowed, and in some sensitive areas (e.g., the Florida Keys), the simple act of hanging clothing on mangrove branches can invoke a civil penalty (*Miami Herald*, 22 March 1990).

Notwithstanding a variety of protective Federal, State, and local laws, the health and diversity of mangroves continue to diminish. Among the principal causes are (1) reduction of freshwater sheet flow into mangroves, mainly by road and drainage canal barriers; (2) legally permitted development in those mangrove habitats with restricted tidal inundation; (3) mitigation rules that promote the establishment of a single habitat type, the fringing red mangrove forest; (4) competitive domination by exotic tree species such as the Australian pine and Brazilian pepper; and (5) severe freezes such as the freeze of 19 December 1989, which killed large areas of mangroves along the Southeast Florida coast. Thus, even though Florida's mangroves are protected, the health, vitality, and perpetuation of this diverse coastal habitat is by no

means assured. From this perspective, any future human activities resulting in regional environmental damage, whether acute or chronic, could place South Florida mangroves and dependent fisheries at risk.

Basic information needs concerning mangroves in South Florida have been reviewed by Snedaker (1989). The following discussion, extracted from an unreferenced document prepared by the author for the National Marine Fisheries Service and the Sea Grant program, highlights two topics of particular interest: (1) the ecological role of dissolved organic matter in the maintenance and regulation of estuarine animal populations; and (2) the habitat requirements, population dynamics, and importance to nearshore fisheries of the white mangrove *Laguncularia racemosa.*

Past research on the ecological role of mangrove detritus has focused almost exclusively on whole leaves and large particulate debris. The results of more recent research, particularly in biological oceanography, indicate that chemically complex DOM may have greater ecological significance than bulk leaf matter. High priority should be accorded to research programs that evaluate the significance of DOM in (1) sustaining an alternate food web based on heterotrophic microorganisms; (2) providing an organic flocculant of benefit to benthic feeders; and (3) generating chemical cues that may regulate the presence and absence of estuarine species (and therefore the predictable spatial and temporal patterns of marine life in estuaries).

Knowledge of the basic autecology of the Caribbean red and black mangroves (*Rhizophora* and *Avicennia*, respectively) is reasonably well developed. In contrast, there is little information available concerning the white mangrove *Laguncularia racemosa.* This species appears to tolerate lower salinities and more anoxic sediments than the other species, and thus occupies a well-defined niche in the mangrove community mosaic. It is also reputed to have high rates of growth and to produce large quantities of leaf detritus, the fate of which is unknown. Research is needed that addresses the specific habitat requirements and population dynamics of the white mangrove, as well as its ecological importance to estuarine and terrestrial animals.

Research needs pertaining to mangroves and oil spills are presented at the end of **Chapter 15.** A more general research topic that applies to all potential sources of environmental damage to mangroves is the susceptibility of stress-adapted mangroves to increased stress. Most mangroves within the study area grow under less-than-optimum conditions and can be classified as stressed. The best examples are the dwarf and stunted mangroves that are common to southeastern Dade County and the Florida Keys. Presumably, the stresses consist of one or more of the following physical characteristics of those environments: inherently low site fertility, minimal or irregular exposure to freshwater runoff and its entrained load of terrigenous nutrients, absence of tidal inundation during the 4- to 6-month low-water season, and/or episodes of extreme hypersaline conditions. Although stressed, these mangroves perform all of the functions and processes associated with unstressed mangroves, notwithstanding their low population density, rates of primary productivity, and standing stock biomass.

A key ecological question concerning these stressed trees is whether or not in their stressed state they are resistant or susceptible to added stress. Specifically, one could argue that these mangroves have "adapted" to the ambient stresses, and that capability to cope with stress gives them a measure of resistance; in other words, they are more hardy than unstressed trees. Conversely, an equally strong argument could be made that these stressed mangroves exist close to the limits of survival, and that any additional drain of metabolic resources would lead either slowly or quickly to the eventual loss of the affected population.

In the context of oil spill assessments and experiments involving mangroves, all of the work appears to have focused on unstressed, or normal, mangroves. Furthermore, there is inadequate information in the extant literature that would allow speculation on the differential responses by normal and stressed mangroves to additive stresses.

CORAL REEFS

Walter C. Jaap and Pamela Hallock

Introduction

Coral reefs are recognized for their beauty and exceptional variety of life. In reef communities, like forest communities on land, the dominant organisms provide other members of the community with food and shelter. The massive and intricate frameworks constructed by reef-building organisms provide an almost infinite array of habitats for other plants and animals, leading to intense biologic activity and high biotic diversity.

Geographic Relationships

Coral reefs of the Florida Keys are similar to Caribbean-Bahamas tropical reefs in species composition and physiographic characteristics. Bank reefs are the major reefal structures; most occur near the continental margin seaward of large islands. Patch reefs are smaller, roughly circular features that occur in waters inshore of the bank reefs.

The coral reefs of the Florida Keys occur at an environmental threshold (Vaughan 1918): they are restricted to south and west of Cape Florida and do not occur on the West Florida shelf (Jaap 1984). Extensive reefs occur offshore of the Florida Keys archipelago (**Figure 4.4**). This chain of islands, which extends from Soldier Key to the Dry Tortugas, exhibits a diverse array of hardgrounds, patch reefs, and bank reefs from 25 m to 13 km (7 nmi) offshore (Jaap 1984). Coral reefs also extend into the Gulf of Mexico from Key West and Smith Shoal to the Content Keys. West and north of the Keys lie a series of shallow embayments (e.g., Biscayne Bay and Florida Bay), the Everglades, and the continental shelf off Southwest Florida. The Straits of Florida and the Florida Current lie beyond the reefs to the south and east.

Coral reef distribution patterns reflect water exchange between the continental shelf and the Atlantic Ocean. Heavy rainfall, drought, summer doldrums, and winter cold fronts influence temperature, salinity, nutrient supply, and turbidity in the shallow bays and sounds and produce waters unfavorable to reef development. Large islands act as barriers to off-shelf transport from Florida Bay and Biscayne Bay; thus Key Largo and Elliott Key have extensive offshore reefs. The island mass from Big Pine Key to Key West is also a barrier to water transport, fostering extensive reef development off this area (Jaap 1984; Shinn et al. 1989). The Middle Keys, which are smaller and separated by numerous wide channels communicating with Florida Bay, have limited reef development. In the Middle and Lower Keys, isolated large corals can be found inside Florida Bay near major passes (Hudson et al. 1989; Smith et al. 1989)

Environmental Characteristics

Coral reefs thrive in relatively warm (18 to 28 °C), clear waters with normal marine salinities (30 to 40 ppt). Environmental conditions, including climate and seawater characteristics in the Florida Keys, are summarized in Schomer and Drew (1982), Jaap (1984), and Jaap and Hallock (in press). Walton et al. (1985) modeled the water column dynamics off Key Largo. Lee (1989) summarized the physical oceanography in the Straits of Florida and eastern Gulf of Mexico.

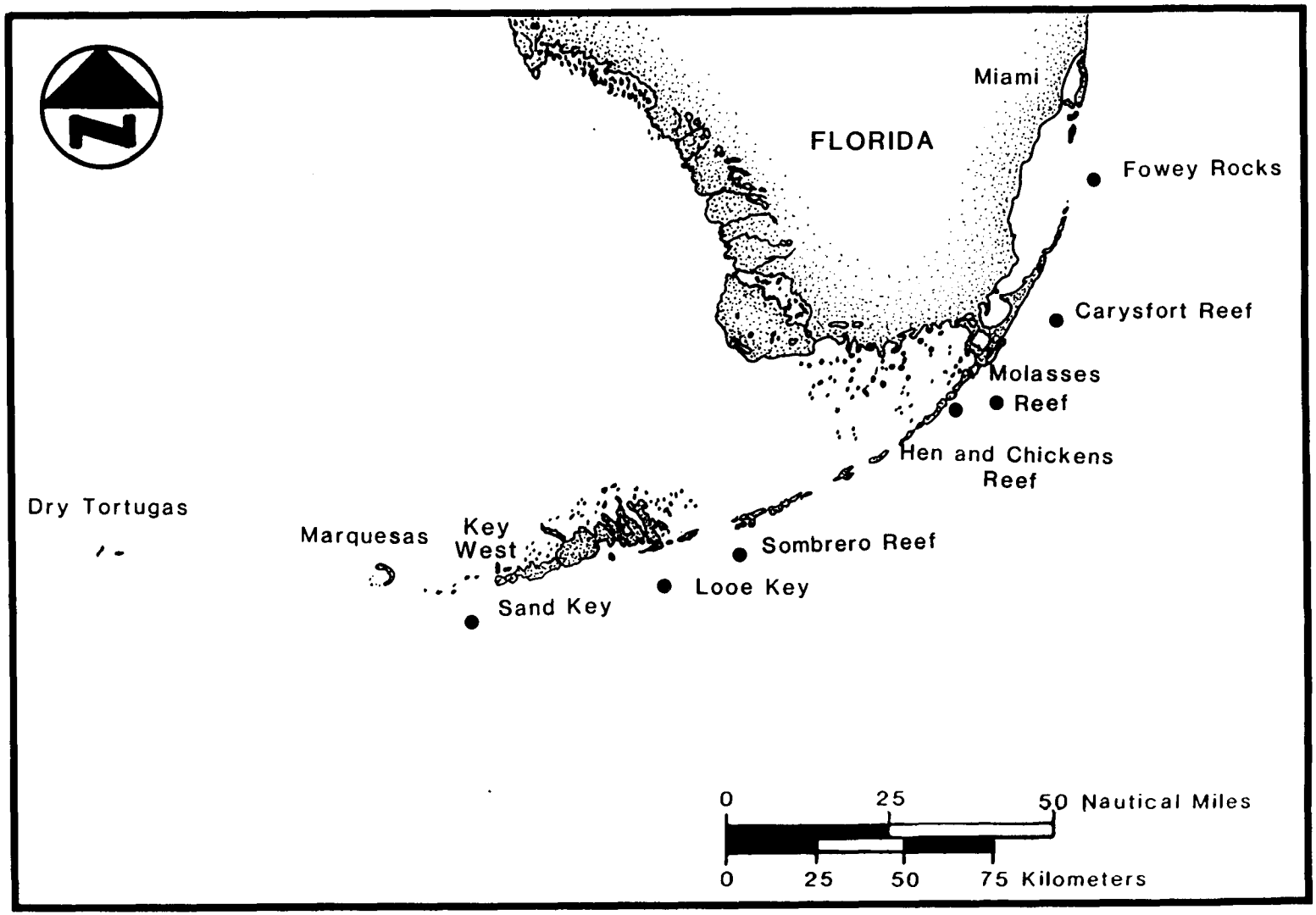


Figure 4.4. Major reefs of the Florida Reef Tract.

Clear waters are crucial to reef-building corals because their microscopic symbiotic algae (zooxanthellae) require sunlight. The clearer the water, the deeper corals can live (Wells 1956, 1957). Water transparency over Florida reefs can vary considerably, from nearly opaque following storms, to exceptional clarity during prolonged calm (Jaap 1984). Plankton, suspended organic matter, and suspended sediments all diminish water transparency. Corals derive nutrients from symbiotic dinoflagellate algae (zooxanthellae) that require light. Thus, growth rates of coral and other reef organisms dependent upon photosynthesis decline as light decreases with depth (summarized by Huston 1985a) or reduced water transparency (Tomascik and Sander 1985). Kanwisher and Wainwright (1967) estimated that zooxanthellate corals require a minimum of about 4% of surface radiation for reef development. These corals need at least 0.15% for survival (Reed 1985). Data on water transparency in the Florida Keys area (Hanson and Poindexter 1972, summarized by Jaap 1984) are consistent with the observation that reef growth in the Keys normally occurs to depths of about 35 to 40 m (Jameson 1981).

Literature Review

Ecologic studies of Florida Keys coral reefs began during the late 19th century (Agassiz 1883; Mayer 1914; Vaughan 1915, 1918; Longley and Hildebrand 1941). Since the Carnegie Laboratory (on Loggerhead Key, Dry Tortugas) burned in 1937, laboratory facilities in the Florida Keys have been lacking until quite recently. Thus, our understanding of Florida corals and reefs relies heavily upon studies from other Caribbean and western Atlantic areas.

Tropical coral reefs are characterized by high species diversity (Loya 1972; Connell 1978; Huston 1985b); rapid recycling of nitrogen and phosphorus (Pilson and Betzer 1973; Webb et al. 1975; Muscatine 1980; Johannes et al. 1983); high gross primary productivity and low net primary productivity resulting from high respiration rates (Lewis 1977; Atkinson and Grigg 1984; Gladfelter 1985; Kinsey 1985); highly transparent water (Wells 1957; Yonge 1963; Wethey and Porter 1976); many species with specialized food requirements, narrow niches, and complex life cycles (Ebbs 1966; Colin 1976; Kissling and Taylor 1977); symbiotic relationships (Limbaugh 1961; Goreau and Hartman 1966; Meyer et al. 1983); and primary productivity by microscopic symbiotic algae (zooxanthellae) living within reef-dwelling Cnidaria (Goreau and Goreau 1960; Chalker 1983; Porter et al. 1984).

Because this section can only highlight certain aspects of the Florida Keys coral reefs, the following brief bibliography is provided. Geological background is presented by Hoffmeister (1974) and Shinn (1984, 1988) (the geology of the Florida Keys is discussed in **Chapter 2**). Synoptic overviews of South Florida coral reefs are found in Multer (1971), Bright et al. (1981), Jaap (1984), Jones et al. (1986), Porter (1987), Voss (1988), and Shinn et al. (1989). General guides to western Atlantic coral reefs include those by Colin (1978) and Kaplan (1982). The four volumes of *Biology and Geology of Coral Reefs* (Jones and Endean 1973-1977) cover a wide spectrum of reef science, as do the Proceedings of the International Coral Reef Symposia (Mukudan and Pillai 1972; Cameron et al. 1974; Taylor 1977; Gomez et al. 1981; Delesalle et al. 1985; Choat et al. 1988). Deep reef surveys off Key Largo are presented by Jameson (1981). The three volume series by Wells (1988) summarizes reef resources and management issues for 109 countries including the U.S. Marine invertebrates inhabiting Florida reefs are identified in Zeiller (1974) and Voss (1976). Field guides to coral reef fish are provided by Chaplin and Scott (1972), Greenberg (1977), and Stokes and Stokes (1980). A diver's guide to the Florida Keys by Halas et al. (1984) contributes practical information on reef diving sites.

Coral Biology

Taxonomy and Life Histories

Reef corals belong to two classes of the Phylum Cnidaria (Coelenterata): Hydrozoa and Anthozoa. Most reef-dwelling members of both classes host zooxanthellae, endosymbiotic dinoflagellate algae of the genus *Symbiodinium* (Blank and Trench 1985) and are therefore dependent upon ample light for photosynthesis. In the Florida Keys, *Millepora* (fire coral) is the only hydrozoan coral on shallow reefs (<30 m); *Stylaster* and *Distichopora* occur in deep reef habitats. Anthozoans include octocorals and stony corals (discussed below), as well as zoanthids, corallimorpharians (false corals), and anemones. Most reef corals are colonial organisms, each made up of thousands of genetically identical members or polyps.

Fire Corals. Two species of fire corals occur on Florida reefs. *Millepora complanata*, the bladed fire coral, is a keel-shaped species restricted to shallow windward reef tops. Mergner (1977) found that this species is restricted to turbulent and highly illuminated reef habitats. Crenulated fire coral (*M. alcicornis*) is a branching species found in a much wider range of reef habitats. The name "fire" coral comes from the burning sensation inflicted by nematocysts (microscopic stinging organs) within the organism's tissues. The animal secretes a limestone skeleton with microscopic pores in which the individuals (zooids) live. A porous skeleton contains tissues with dense concentrations of zooxanthellae that provide most of the energy needed by the colony. The golden-yellow color of the fire coral comes from these microscopic algae.

Octocorals. Octocorals, which include sea whips, sea plumes, sea fans, gorgonians, and soft corals, are a conspicuous and diverse faunal element on most Florida Keys reefs; 42 species have been recorded (Jaap 1984). Octocorals, which have polyps bearing eight tentacles, vary in form from irregular mats to large sea fans; polyps are distributed along the branches, fan surfaces, or mats. Organic skeletons are commonly reinforced by calcareous spicules, which are secreted by the polyps. Taxonomy of octocorals is based upon the microscopic morphology of the spicules (Bayer 1961). After death and organic decay of a colony, the spicules become part of the sand-sized sediments of the reef.

Life histories of most octocoral species are poorly known. One species, *Plexaura homomalla*, has been intensively studied in the Cayman Islands (Kinzie 1974). Colonies become sexually mature at 25 to 35 mm in height. Male individuals release sperm into the water, and fertilization occurs within the female polyps. Larvae spend a brief time in the plankton before settling on appropriate substrata and starting new colonies. Growth rates vary from 10 to 40 mm/year.

Octocorals are extremely abundant in some Florida reef habitats, occurring in densities up to 50 colonies/m^2 (Opresko 1973; Wheaton and Jaap 1988). Many octocoral species inhabit shallow patch reef and bank reef habitats in areas with substantial turbulence and high light intensities. Highest rates of mortality occur during larval and juvenile life stages. Mortality is also high among adult colonies dislodged by storms. Invertebrate predators include the snails *Cyphoma gibbosum* and *Coralliophila caribaea* and the fire worm *Hermodice carunculata*. Black band disease is a pathogen in some octocorals (Feingold 1988).

Stony Corals. The Scleractinia, or stony corals, include common reef-building species. Sixty-three taxa (species and subspecies or forma), living at depths of <1 to 45 m, have been recognized in the Florida Keys (**Table 4.3**). Taxonomy is based on external skeletal morphology and calyx characteristics (Vaughan and Wells 1943; Wells 1956; Zlatarski and Estalella 1982). Growth forms include *branching*, *hemispherical*, *plates*,

Table 4.3. Scleractinian corals of the Florida Reef Tract.

Suborder Astrocoeniina Vaughan and Wells

Family Astrocoeniidae Koby
Stephanocoenia michelinii (Milne Edwards and Haime)

Family Pocilloporidae Gray
Madracis decactis (Lyman)
M. formosa Wells
M. mirabilis (sensu Wells)

Family Acroporidae Verrill
Acropora palmata (Lamarck)
A. cervicornis (Lamarck)
A. prolifera (Lamarck)

Suborder Fungiina (Verrill)

Family Agariciidae Gray
Agaricia agaricites (Linne)
A. agaricites danai Milne Edwards and Haime
A. agaricites carinata Wells
A. agaricites purpurea (LeSueur)
A. lamarcki Milne Edwards and Haime
A. undata (Ellis and Solander)
A. fragilis (Dana)
Leptoseris cucullata (Ellis and Solander)

Family Siderastreidae Vaughan and Wells
Siderastrea radians (Pallas)
S. siderea (Ellis and Solander)

Family Poritidae Gray
Porites astreoides (Lamarck)
P. porites (Pallas)
P. porites divaricata LeSueur
P. porites furcata Lamarck
P. porites clavaria Lamarck
P. branneri Rathbun

Suborder Faviina Vaughan and Wells

Family Faviidae Gregory
Favia fragum (Esper)
F. gravida (Verrill)
Diploria labyrinthiformis (Linne)
D. clivosa (Ellis and Solander)
D. strigosa (Dana)
Manicina areolata (Linne)
M. areolata mayori Wells
Colpophyllia natans (Houttyn)
C. amaranthus (Muller)
C. breviseralis Milne Edwards and Haime
Cladocora arbuscula (LeSueur)
Montastraea annularis (Ellis and Solander)
Solenastrea hyades (Dana)
S. bournoni Milne Edwards and Haime

Suborder Faviina (Continued)

Family Rhizangiidae d'Orbigny
Astrangia astreiformis (Milne Edwards and Haime)
A. solitaria (LeSueur)
Phyllangia americana Milne Edwards and Haime

Family Oculinidae Gray
Oculina diffusa Lamarck
O. varicosa LeSueur
O. robusta Pourtales

Family Meandrinidae Gray
Meandrina meandrites (Linne)
M. meandrites brasiliensis (Milne Edwards and Haime)
Dichocoenia stellaris Milne Edwards and Haime
D. stokesii Milne Edwards and Haime
Dendrogyra cylindrus Ehrenberg

Family Mussidae Ortman
Mussa angulosa (Pallas)
Scolymia lacera (Pallas)
S. cubensis (Milne Edwards and Haime)
Isophyllia sinuosa (Ellis and Solander)
I. multiflora Verrill
Isophyllastraea rigida (Dana)
Mycetophyllia lamarckiana Milne Edwards and Haime
M. danaana Milne Edwards and Haime
M. ferox Wells
M. aliciae Wells

Suborder Caryophylliina Vaughan and Wells

Family Caryophylliidae Gray
Eusmilia fastigiata (Pallas)
Paracyathus pulchellus (Philippi)

Suborder Dendrophylliina Vaughan and Wells

Family Dendrophylliidae Gray
Balanophyllia floridana Pourtales

columns, *encrusting*, and *fronds*. Stony coral generation times vary greatly, ranging from a few years in small, finger corals to hundreds of years in massive star and brain corals. In these larger corals, multiple generations of polyps coexist. Sexual maturity seems to depend upon both size and age of a colony. Large, sexually mature colonies, if broken into small fragments, cease gamete production until they grow to a minimum size (Kojis and Quinn 1984; Szmant-Froelich 1985).

Among stony coral species, internal fertilization, external fertilization, broadcasting of gametes, and larval brooding all have been reported (Fadlallah 1983). After fertilization and embryonic development, free-living planula larvae are formed, which can be either planktonic or benthic. After periods that vary from species to species and also with environmental conditions, the larvae settle and metamorphose into juvenile corals. A larva attaches itself to the substratum by secreting a basal plate, the initial skeletal structure. Walls and axial structures are secreted next (Wells 1956). Growth involves a harmonious integrated increase in coral tissue, zooxanthellae, and skeleton (Barnes 1973). When the larva is fully transformed into a polyp, growth proceeds with the budding of daughter polyps by asexual division.

Growth rates of Florida's reef-building corals have not been studied extensively (e.g., Landon 1975). Almost all growth rate evaluations focus on a very few species (*Acropora cervicornis*, *Diploria strigosa*, and *Montastraea annularis*). Growth rates of the 40 or more other species are poorly known. X-ray photographs of *M. annularis* reveal annual growth rings which can be used to determine growth and environmental conditions (Hudson et al. 1976; Hudson 1981). Growth rate in this massive, head-forming species is relatively slow; growth rates averaged 8.2 mm/year on nearshore patch reefs, and 6.3 mm/year in offshore waters deeper than 6 m. Maximum growth rates of <11 mm/year occurred in waters <3 m deep. For other head corals, Ghiold and Enos (1982) found that the brain coral *D. labyrinthiformis* in the Key Largo area grow at a rate of about 3.5 mm/year and Landon (1975) reported a growth rate of 2.4 mm/year for *Siderastrea siderea*. Thus, head corals grow so slowly that 1-m-high heads are approximately 100 years old (Shinn et al. 1989). In contrast, growth rates of the branching coral *A. cervicornis* (staghorn coral) can exceed 100 mm/year (Shinn 1966). Shinn (1976) found that branches form annually during winter months, and that each branch may grow as much as 10 cm during the following year. However, because branching corals do not produce the dense accumulations of limestone, apparent differences in growth rate are primarily the result of growth form and geometry. Other available growth data include *Porites porites* at Sambo Reef, 16 mm/year (Landon 1975); *Dendrogyra cylindrus* at Elliott Key, 5 mm/year (Hudson unpubl. data as reported by Shinn et al. 1989); and *Solenastrea bournoni*, 8.9 mm/year (Hudson et al. 1989).

Productivity and Calcification

Healthy, well-developed reefs thrive in clear, nutrient-depleted waters (Birkeland 1987). The symbiotic relationship between corals and their zooxanthellae allows efficient recycling of nutrients between host and symbiont (Muscatine and Porter 1977), providing corals with a competitive advantage over algae and animals lacking symbionts when nutrients are scarce (Hallock 1981). More abundant nutrients stimulate benthic algal growth; overgrowth by benthic algae is harmful to living corals (e.g., Smith et al. 1981) and inhibits coral recruitment (Birkeland 1977). Abundant nutrients also enhance plankton growth, which diminishes water transparency. The fewer nutrients in seawater, the clearer it is and the deeper corals can live. Furthermore, increased plankton abundances favor larval survival, recruitment, and growth of coral predators, competitors, and bioeroders (Hallock and Schlager 1986).

Nutrient levels in surface waters of the Florida Reef Tract can vary from barely detectable to more than 1 μM inorganic phosphorus and 3 μM inorganic fixed nitrogen (Skinner and Corcoran 1989). There is disagreement over which nutrient, fixed nitrogen or phosphate, limits coral growth (Gladfelter 1985). In Skinner and Corcoran's data, the lowest nitrogen values are often accompanied by relatively high phosphate levels and *vice versa*, indicating that either may be limiting under certain circumstances. Studies at Looe Key showed that ambient phosphate and nitrate in the reef areas ranged from 0.1 to 0.2 μM and 0.5 to 1.0 μM, respectively (Littler et al. 1986). Unusual upwelling events during late spring and early summer stratify the water column with respect to nutrients and temperature at Looe Key and elevate phosphate and nitrate concentrations in the water column (Lapointe and Smith 1987). Crossland (1983) noted that sub-tropical sea-surface waters typically contain <0.3 μM inorganic phosphorus and <1 μM inorganic fixed nitrogen.

Thus, while nutrient concentrations in the waters of the Florida Reef Tract are similar to those typical of subtropical waters, Florida waters are prone to nutrient pulses that can be detrimental to reef growth (Margalef 1968). Hallock (1988) suggested that the near-threshold position of the Florida Keys reefs is as much a factor of excess nutrients as of winter temperatures. As human populations have increased in South Florida, nutrient loading has inevitably increased in waters of the Florida Reef Tract. Both Voss (1973) and Dustan (1977a), in non-technical papers, suggested that sewage pollution was damaging the reefs of the Florida Keys. The classic study of how nutrient pollution can damage a coral reef was reported by Smith et al. (1981) for Kaneohe Bay, Hawaii. Tomascik and Sander (1985) reported similar decline of Barbados reefs as a result of sewage pollution. Shinn (1988) identified excess nutrients as the most probable underlying cause of the serious decline in living corals in recent years. Following Lapointe and O'Connell's (1988) report that use of septic tanks and shallow injection wells in the porous limestones of the Florida Keys is accelerating eutrophication of surface waters, a workshop on coral reef research and management in the Florida Keys in June 1988 concluded that excessive nutrients from nearby land masses and Florida Bay are seriously threatening the Florida Reef Tract (Miller 1988).

Although corals are animals, they function as primary producers in the reef system via their zooxanthellae. Most corals are also highly specialized predators (Yonge 1930) and capture zooplankton from the water column. Some species ingest bacteria from seawater (Di Salvo 1971); some can feed on dissolved organics in seawater (Stephens 1962); and some feed on detritus (Goreau and Goreau 1960). Many species even digest the tissues of other coral species using mesenterial filaments (Lang 1971, 1973), although this is primarily a form of competition, not predation. Despite the variety of sources, direct feeding may supply $<10\%$ of the corals' energy needs (Muscatine and Porter 1977). In such cases, most energy comes from photosynthesis by zooxanthellae (Kanwisher and Wainwright 1967; Lewis 1977; Gladfelter 1983, 1985; Chalker et al. 1984; Kinsey 1985). Zooxanthellae, in turn, get nutrients from metabolic waste products of the coral host as well as from seawater or detritus. Thus, the coral-symbiont system is specialized to concentrate scarce and dispersed nutrients from a variety of sources and to use them for maintenance, growth, and reproduction.

Photosynthesis by zooxanthellae also promotes production of skeletal limestones that make up the reef framework (Kawaguti and Sakumoto 1948; Goreau 1959). Zooxanthellae provide coral with energy for calcification. Reef corals calcify at significantly higher rates in light than in dark, and carbon produced by the zooxanthellae is translocated to growth areas which lack zooxanthellae (Goreau and Goreau 1959a,b). Calcium ion transport is enhanced by the enzyme carbonic anhydrase, which requires expenditure of energy (Isa and Yamazato 1984). Growth in branching *Acropora* spp. is the integration of three processes: (1) linear extension of an axial corallite at the branch

tip; (2) radial growth or increase in diameter of the branch; and (3) internal calcification or infilling of space within a branch (Gladfelter 1982). The first phase occurs in the dark, the other phases occur in the light and at rates two to three times greater than the first phase (Barnes and Crossland 1980). Mass calcium accretion is correlated with number of sun hours (Gladfelter 1984). Coral growth is independent of plankton supply and is significantly reduced by shade (Wellington 1982). Zooxanthellae may also prevent phosphate poisoning of coral calcification by removing phosphatic wastes and any phosphates in the microenvironment; phosphate inhibits precipitation of aragonite crystals (Simkiss 1964; Mucci 1986), the skeletal building blocks of corals.

Biological Interactions

Complex biological interactions are particularly characteristic of coral reef communities. In addition to such common processes as grazing and predation, typical interactions on coral reefs include disease, bioerosion, competition, chemical "warfare," and symbioses.

A variety of disease pathogens may injure or kill corals (Antonius 1974, 1976, 1981a,b; Mitchell and Chet 1975; Ducklow and Mitchell 1979) and other reef-associated organisms. Shinn (1988) has argued that, in the Florida Keys, destruction by diseases is far more devastating and long lasting than mechanical damage. Shinn contends that the disease outbreaks may be associated with nutrient loading and other anthropogenic and natural stresses.

The most common coral pathogen is "black band" disease (*Phormidium corallyticum*: Cyanobacterium: Oscillatoriaceae), which was originally described by Antonius (1974) and subsequently studied by Dustan (1977b), Rützler and Santavy (1983), Rützler et al. (1983), and Taylor (1983). The cyanobacterium often invades massive corals following structural damage to tissues. This disease killed many large, old colonies of *Montastraea annularis* at Carysfort Reef between 1978 and 1985, and is now rampant at Looe Key Reef (Shinn et al. 1989). Other coral pathogens include bacterial infections such as "white band" disease (Peters et al. 1983; Peters 1984) and fungi (Ramos 1983; Jaap 1985; Te Strake et al. 1988). Neoplasms (calicoblastic epithelioma) were found in populations of elkhorn coral (*Acropora palmata*) at Carysfort Reef and Grecian Rocks (Peters et al. 1986). Overcrowding may increase incidence of disease (Gladfelter 1982; Peters et al. 1983). *Entocladia*, a microalga, infects the octocoral *Pseudoplexaura*, producing galls that weaken the skeletal structure (Goldberg et al. 1985). An epidemic bacterial disease decimated black sea urchin (*Diadema antillarum*) populations throughout the Caribbean and Florida Keys during 1983 to 1984 (Bak et al. 1984; Lessios et al. 1984a,b; Bauer and Agerter 1987).

Florida reefs, which exist at the climatic threshold for western Atlantic reef environments, also live a marginal existence in the interplay between limestone production by corals and coralline algae, and destruction by biological and physical processes. Some organisms chemically or mechanically break down reef limestone, a process known as bioerosion (Neumann 1966). Bioeroders include such diverse groups as parrotfish that bite off bits of coral and coralline algae, *Diadema* echinoids that erode the limestone as they graze algae, and boring organisms such as endolithic bivalves, clionid sponges, a variety of polychaete and sipunculid worms (Bromley 1978; Risk and MacGeachy 1978), and microorganisms (Golubic et al. 1975). Bioeroders sculpt reef morphology, providing holes and spaces for a diverse array of organisms (Warme 1975). Many of these organisms, particularly the sponges, echinoids, and bivalves, are capable of erosion rates that equal or exceed rates of reef growth (Bromley 1978; Risk and MacGeachy 1978; James and Macintyre 1985). In a healthy reef system, abundances of

bioeroders and other fauna are apparently limited by the normally scarce food supplies, but where nutrients and food are more readily available, their abundances increase sharply (e.g., Smith et al. 1981; Rose and Risk 1985). Hein and Risk (1975) reported that, in mature coral heads in the Florida Keys, rate of bioerosion approximately equals the rate of skeletogenesis. Hudson (1977) estimated that rates of bioerosion in dead *M. annularis* heads were sufficient to reduce a solid, 1-m-high head to rubble in 150 years.

Competitive interactions include overgrowth of understory species by species with rapid growth rates (e.g., the stony coral *Acropora cervicornis*) (Shinn 1976; Jaap et al. 1989). Birkeland (1977) demonstrated experimentally that coral recruitment is inversely related to nutrient supply; when nutrients are plentiful, filamentous algae, barnacles and bryozoans outcompete coral larvae for space. Some bryozoa can overgrow other sessile reef organisms (Buss 1980). Under low light conditions, sponges are very successful competitors for space (Bryan 1973; Vicente 1978; Jackson and Winston 1982). Fire corals are successful in colonizing living octocoral branches (Whale 1980). Scleractinian corals expand and defend territory by digestion of adjacent coral tissues through use of mesenterial filaments (Lang 1971, 1973). Other coral species defend themselves from such attack with specialized sweeper tentacles (den Hartog 1977; Richardson et al. 1979; Wellington 1980; Bak et al. 1982; Chornesky and Williams 1983). Allelopathy, or chemical defense and offense, is another mechanism used by some organisms, particularly octocorals, to prevent overgrowth and gain living space (Cameron 1974; Glynn 1980; Bak et al. 1981; Tursch 1982; Sullivan et al. 1983).

Grazing organisms also play important roles in coral reef communities. For example, damselfish (*Pomacentrus planifrons*) destroy coral tissue and farm algae on dead coral (Kaufman 1977; Brawley and Adey 1981; De Ruytor 1984). Black sea urchins graze algae from the reef, as well as from areas adjacent to the reef (Sammarco et al. 1974; Bak and Van Eys 1975; Ogden and Lobel 1978), providing settlement habitat for coral larvae by exposing clean limestone substrate (Sammarco 1980).

Coral predators are also numerous and diverse. The marine worm *Hermodice carunculata* feeds on numerous coral species, including staghorn coral (Marsden 1960, 1962; Glynn 1962; Ebbs 1966; Antonius 1974; Lizama and Blanquet 1975). Gastropod molluscs known to feed on corals include *Coralliophila abbreviata*, *Calliostoma javanicum*, and *Cyphoma gibbosum* (Glynn 1964, 1973; Robertson 1970; Ott and Lewis 1972). Fish that feed on corals include parrotfish (Scaridae), spadefish (Ephippidae), damselfish (Pomacentridae), and butterflyfish (Chaetodontidae) (Glynn 1973).

Sponges also interact with the coral reef in ways other than bioerosion and competition for space (e.g., Goreau and Hartman 1963; Schmahl 1984). Some sponges bind coral skeletons to the reef substrate (Wulff and Buss 1979; Wulff 1984); some sponges protect the coral undersurface from attacks by boring organisms (Goreau and Hartman 1966).

Numerous organisms are highly specialized to live in close association with corals, gaining shelter and food, and often devouring mucus that is prevalent on the coral tissue surface. Examples include copepods with worm-like bodies (Patton 1976), and the crab *Domecia acanthophora* and some pyrogomatid barnacles that induce coral skeletons to grow around them, forming a shelter for the symbiont (Patton 1967).

Reef Communities

Community Structure

Coral reefs are often compared to tropical rain forests in the way space and resources are stratified: canopy, understory, and substory. As the principal builders of the reef system, corals are the principal source of spatial complexity and shelter. Literally hundreds of species of protists, macrophytes, invertebrates, and fish are known to live in the Florida Reef Tract. Complexity is further enhanced by transitory animals such as fish, birds, and turtles that feed, breed, or seek temporary shelter on coral reefs. Floating algae, with associated organisms, are also transitory constituents.

Stony corals, together with some octocorals and larger sponges, form the canopy. Branching corals, as well as the reef framework, provide shelter for fish that feed upon the plankton in the overlying water column. Fish are analogous to the small birds and bats that dwell in the forest canopy and venture out to feed on insects. The coral canopy provides shelter from larger predators, such as sharks and barracuda, that prowl the reef margins. The reef also provides shelter for organisms, such as lobsters, that hunt in seagrasses behind the reef. There is mutual benefit to the reef and the organisms that seek refuge in the reef. Fish and crustaceans transfer nutrients and organic matter, via their excreta, from the water column or seagrass flat to the reef (Faulkner and Chesher 1979; Meyer et al. 1983). These nutrients and organic matter are therefore available to corals and algae living in the understory, but do not promote phytoplankton growth in the overlying water column--growth that would reduce light reaching the benthos.

Understory biota, including photosynthetic organisms such as algae, sponges, ascidians, and foraminifera that harbor algal symbionts, all contribute to the organic productivity of the reef while benefiting from the nutrients brought in by mobile organisms. These and other epibenthic organisms, such as polychaetes and bryozoans, dwell upon the dead portions of the coral surface.

Substory biota (cryptofauna) live within the coral framework. Smaller caves are occupied by crustaceans, molluscs, ophiuroid echinoderms (brittle stars), fish, and polychaete and sipunculid worms. Larger, deeper excavations, often found at the reef base, provide shelter for fish, crabs, and lobsters. The excavations also provide surfaces on and within the reef for sessile organisms, such as bryozoans, ascidians, and serpulid worms. Cryptic biota inhabiting coral rubble interstices in Biscayne National Park includes at least 80 species (bryozoa, coralline algae, foraminifera, molluscs, polychaetes, sipunculids, sponges, and tunicates); maximum species diversity occurs between 20 and 30 m in the fore-reef slope; water motion and sediment texture are important factors influencing species distributions (Choi and Ginsburg 1983).

Diversity

Biogeographic and environmental factors determine how many and which species occur on a particular reef. The diversity of organisms on a healthy Florida reef is not as high as that of a comparable western Pacific reef simply because West Indian reef biotas have declined in diversity more during the past 15 million years than have Indo-West Pacific biotas (Frost 1977). Because Florida's reefs are located near the northern limit of West Indian biotas, their diversities are further diminished relative to comparable central Caribbean reefs, e.g., those of the Cayman Islands. The actual number of plant and animal species on a particular reef at a point in time is primarily controlled by local environmental factors, such as water transparency, spatial

heterogeneity, depth, age of the reef, frequency and magnitude of physical disturbance (environmental predictability), and organismal life histories (Grassle 1973).

To date, no one has completed an intensive investigation of floral and faunal diversity of a single Florida reef. Voss (1983) reported 62 algal species, 3 seagrasses, 55 sponges, 73 cnidarians, 22 polychaete worms, 67 molluscs, 37 crustaceans, 7 tunicates, and 224 fish species from the Key Largo area, including sedimentary, seagrass, live bottom, and coral reef habitats. Those numbers represent only a small fraction of the species that actually live there. Kissling (1977) reported 420 invertebrates from nine reefs off the Lower Florida Keys. Longley and Hildebrand (1941) listed 442 species of fish from Dry Tortugas and Starck (1968) reported 517 fish species from Alligator Reef.

Spatial heterogeneity is an obvious factor controlling reef diversity; more kinds of microhabitats support more species (Wells 1957; Grassle 1973). Depth, water transparency, and age of the reef influence spatial heterogeneity. Coral species show depth zonation: branching species thrive in relatively shallow water where at least 60% of surface light is available; star and brain corals flourish down to 20% of surface light (Huston 1985a); and plate corals can occur at depths with as little as 0.15% of surface light (Reed 1985). On a Florida Keys reef, the depths to which those light levels are available are approximately 5, 15, and more than 43 m, respectively (calculated from values reported by Jaap 1984). On a mature reef, three-dimensional spatial heterogeneity is well developed in the massive head-coral zone, possibly declining somewhat upward into the branching-coral zone and declining substantially with increasing depth as massive head corals give way to low-lying plate corals. Topography of the original substratum upon which the reef grew can also influence spatial heterogeneity.

Environmental predictability is also a major factor creating depth-related diversity gradients. Though spatial heterogeneity on a shallow, reef margin may be comparable to that of the deeper head-coral zone, lack of environmental predictability limits diversity on the shallow margin. Ultraviolet radiation, thermal extremes, desiccation during extremely low spring tides, high wave energy, and abrasion by sediments carried by storm waves all act to reduce diversity. Connell's (1978) intermediate magnitude and frequency disturbance model, when applied to Florida's reefs, indicates that disturbance occurs at such magnitude and frequency to prevent development of highly diverse reef communities at depths <2 m.

For the Caribbean in general, coral and algal species diversity increases from the reef crest to maxima at depths of 20 to 30 m (Huston 1985b). Because light penetrates only about half as deeply on Florida's reefs as on many other Caribbean reefs, maximum diversity is expected at about 8 to 15 m.

Major Reef Types

The region of reef development seaward of the Florida Keys is 270 km (146 nmi) long (Fowey Rocks to Marquesas Keys). There are 96 km (52 nmi) of bank reef habitat and 6,000 individual patch reefs (Marszalek et al. 1977). The Upper and Lower Keys have greater reef development than the Middle Keys area (Marszalek et al. 1977; Shinn et al. 1989).

Bank Reefs. Bank reefs occur 7.4 to 13 km (4 to 7 nmi) seaward of the Florida Keys, paralleling the coast and continental shelf margin. Major bank reefs are shown in **Figure 4.4.** Most occur off Key Largo and from Big Pine Key to Key West where major islands protect the reefs from the detrimental influence of Florida Bay waters. A reef flat is located on the inshore side of the reefs. This relatively barren area is characterized by coral rubble encrusted by coralline algae and mustard hill coral (*Porites*

astreoides). Waves, intensive solar radiation, and frequent tidal exposure severely limit the reef-flat community. Shoreward, the reef flat grades into a mosaic of sedimentary or seagrass habitats (Shinn et al. 1989).

Spur-and-groove formations are a principal characteristic of bank reefs. Spurs are elongate reefal limestone formations covered with living corals. Grooves are valleys containing carbonate sand and rubble that separate the spurs. Spur tops are <1 m deep at shoreward ends and as deep as 10 m at seaward margins; spurs may extend a linear distance of a hundred meters or more. Grooves may be <1 to 4 m deep. Most spur-and-groove formations extend laterally 1 to 2 km (0.5 to 1 nmi) along reefs within the 1- to 10-m depth contours. Spur formations are usually aligned perpendicular to the coast and continental shelf margin. In particular, they face into the predominant wind-sea direction. Where the groove system is present, sediments and water pass through the reef with minimal damage to attached biota.

Spurs are constructional features in Florida reefs (Shinn 1963, 1980; Shinn et al. 1981). The major spur builder is *Acropora palmata* (elkhorn coral) (Shinn 1966). Other corals, algae, and limestone debris fill spaces between *A. palmata* colonies. This species, under optimum environmental conditions, can monopolize large areas (Glynn 1973; Adey 1977). As the population grows upward to low tide level and increases in density, localized reduction in water circulation reduces planktonic food supply and may also influence oxygen and carbon dioxide exchange and sediment removal. When coral growth reaches low tide level, corals die back from environmental stress when exposed. Dead corals are encrusted with coralline algae, producing a pavement upon which other organisms can live. Meanwhile, the *A. palmata* population continues to colonize seaward, building upon the skeletons of deeper-dwelling corals that grew upward into the *A. palmata* zone or upon debris from its own population.

Communities occupying and constructing spurs are zoned by depth; the major controlling parameters are wave energy and water transparency. A guild of 15 to 19 specialized coral and zooanthid species occupies the shallow (<2 m) spur habitats [known as the *Millepora/Palythoa* zone for its dominant species, *Palythoa caribbae* (golden sea mat) and *Millepora complanata* (bladed fire coral)]. Other common members include *Zoanthus sociatus* (green sea mat) and *Ricordea florida* (false coral) (Wheaton and Jaap 1988). These species are adapted to intense solar radiation and high wave energy. Benthic cover can exceed 100% (canopy and understory), and the density of stony corals, principally *Millepora complanata*, ranges from 7.6 to 9.6 colonies/m^2 (Wheaton and Jaap 1988; Jaap et al. 1989).

Acropora palmata dominates between 2 and 5 m depths. *Agaricia agaricites* is abundant on vertical surfaces (spur sides). Diversity increases and dominance of species diminishes with increasing depth. Below 6 m, large heads of *Montastraea annularis* are major contributors to coral cover. Eighteen to 22 stony corals and 7 to 15 octocorals populate deeper spur-and-groove habitats; density of stony corals averages between 9 and 15 colonies/m^2 (Wheaton and Jaap 1988; Dustan 1985; Jaap et. al. 1989).

Some reefs show little or no development seaward of the spur-and-groove zone, whereas others have a well-developed fore-reef that slopes to 30 to 40 m (e.g., Eastern Sambo Reef off Boca Chica). Local topography and reef age may influence fore-reef development. Where fore-reefs are developed, they may be characterized by low relief, spur-and-groove complexes running seaward downslope. Corals are often diverse and abundant, averaging about 8 colonies/m^2 (Wheaton and Jaap 1988; Jaap et al. 1989). Algae, octocorals, and sponges are also common.

The deepest portions of Florida bank reefs are in 37- to 40-m depths (Jaap 1981) and occur as isolated outcrops surrounded by sediments. Species that appear more abundant in this habitat include *Agaricia fragilis*, *Agaricia lamarcki*, *Leptoseris cucullata*, *Madracis decactis*, *Meandrina meandrites* forma *brasiliensis*, *Mycetophyllia aliciae*, and *Mycetophyllia lamarckiana*.

Stony corals were surveyed on several bank reefs in the Florida Keys (Jaap 1984). With the exception of shallow spur-and-groove habitats, there is considerable variability among samples from similar habitats. Intra-reef similarity is usually greater than inter-reef similarity. Temporal change in shallow reefs is high, particularly for small branching or poorly attached species (Shinn 1976; Jaap 1984, 1985; Dustan and Halas 1987; Jaap et al. 1989), because these corals typically recruit by fragmentation (Tunnicliffe 1981).

Patch Reefs. Patch reefs occur throughout most of the Florida Reef Tract (Jones 1977; Marszalek et al. 1977; Davis 1979, 1982). They are the principal reef form between northern Elliott Key and northern Key Largo (**Figure 4.4**) where approximately 5,000 patch reefs occur (Marszalek et al. 1977). Most patch reefs are situated seaward of Hawk Channel and inshore of the outer reef line; exceptions occur between Plantation Key and Newfound Harbor Keys where patch reefs occur close to the coast. Patch reefs, which typically occur in water depths of about 2 to 9 m, are usually roughly circular in outline, and range from 30 to 700 m in diameter.

Patch reefs provide topographic relief and biotic diversity in seagrass and sedimentary habitats. The region directly adjacent to the reef is usually barren because reef-dwelling herbivores venture from the reef to graze algae and seagrasses (Randall et al. 1964; Randall 1965; Sammarco et al. 1974). Local environmental conditions (Jones 1963), physical characteristics, and reef age determine physiography. Smith and Tyler (1975) and Jones (1977) proposed a model that considers the patch reef a superorganism with distinctive life stages. In the initial stage, pioneer corals settle on available hard substrata (rocky outcrops, conch shells, etc.). These pioneers, *Cladocora arbuscula*, *Favia fragum*, *Manicina areolata*, *Porites porites*, and *Siderastrea radians*, are short-lived; however, their skeletal remains provide a foundation upon which the primary framework-building species can settle. Following establishment of these framework builders (which include *Colpophyllia natans*, *Diploria labyrinthiformis*, *Diploria strigosa*, *Montastraea annularis*, and *Siderastrea siderea*), other corals, sponges, algae, and bryozoans begin to settle and occupy the newly created habitats. As the framework corals grow upward, they add to the heterogeneity of the environment, thereby creating additional niches for other plants and animals. The creation of caverns and tunnels by merging of the coral canopy and bioerosion provides habitat for shade-dwelling organisms and shelter for fish and larger mobile invertebrates. Carbonate production on patch reefs was studied by Ghiold and Enos (1982), who estimated potential vertical accretion at 2.2 to 6.6 m per thousand years.

As the reef approaches sea level, growth is limited to lateral expansion. The upper, central portions of older patch reefs are often hardgrounds occupied by dense populations of octocorals. The reef margins are dominated by stony corals. This pattern can be seen in the coral community of Dome Reef patch reef in Biscayne National Park (Jaap 1983, 1984). At the reef periphery, star coral *Montastraea annularis* was the most abundant stony coral, accounting for 17% of all coral colonies and 87% of stony coral cover. In the reef interior, octocorals were the dominant element, while star coral accounted for 7% of all individuals and 55% of stony coral cover.

Dry Tortugas Reefs. Dry Tortugas is composed of islands, shoals, and reefs located about 120 km (65 nmi) west of Key West (**Figure 4.4**) (Davis 1982; Jaap et al. 1989). While Dry Tortugas reefs have many characteristics in common with other South Florida reefs, they are notable for their thickets of branching staghorn coral (*Acropora cervicornis*) that occur west and north of Loggerhead Key. Early work in the region (Agassiz 1883) documented wide distribution of staghorn corals at Dry Tortugas, despite an environmental perturbation that nearly eliminated those corals in 1878 (Mayer 1902). Vaughan (1911) also reported staghorn corals west of Loggerhead Key. Cold temperatures have dramatically reduced staghorn populations at least twice during this century. Populations were reduced by roughly 95% during the winter of 1962-63 and again in 1976-77 when cold fronts lowered temperatures to 14 °C. Mayer (1914) reported the lethal lower thermal tolerance of *A. cervicornis* to be 13.5 to 15 °C. Staghorn coral proliferates during favorable periods by rapid growth and by fragmentation, which propagates new colonies (Tunnicliffe 1981). Populations recovered to form massive thickets of a least 0.5-m relief by 1981 and over 1-m high by 1984.

Live Bottom Communities

Live bottom communities are among the most widely distributed marine communities in Florida waters. They occur from subtidal areas to the continental shelf edge, virtually anywhere that there is solid substratum upon which members of this epibiotic community attach. Attached biota occupy everything from reef limestones to rocky outcrops on the seafloor to artificial reefs, seawalls, buoys, bridge pilings, and boat bottoms. Flora and fauna naturally vary throughout this range of depths and substrata, but algae, sponges, octocorals, hardy stony corals, and bryozoans are often visually dominant. In general, shallow-water (<6 m), live bottom biota throughout Florida show temperate, Carolinian affinities, with tropical West Indian affinities becoming increasingly important to the south (Collard and D'Asaro 1973).

In a remote area northwest of Dry Tortugas (24 ° 47.25' to 25 ° 16.75'N and 83 ° 37.75' to 83 ° 51.00'W) in depths of 64 to 76 m, a zone of highly irregular relief supports an unusual biological assemblage visually dominated by frondose green algae, *Anadyomene menziesii*, and large plates of lettuce coral, *Agaricia* spp. This assemblage was discovered during surveys sponsored by the Minerals Management Service in 1982 (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1985) and may be similar to those found on vertical escarpment habitats of the Bahamas and central Caribbean basin (Ginsburg and James 1973; Goreau and Land 1974; Lang 1974; Reed 1985). This assemblage is discussed further in **Chapter 5.**

The distribution and species composition of live bottom communities offshore Southwest Florida is discussed in reports by Continental Shelf Associates, Inc. (1987, 1989) and Environmental Science and Engineering, Inc. et al. (1987). For further information, see **Chapter 5.**

Deep Coral Banks

Deepwater coral banks occur on the continental slope margins of Florida at depths of 400 to 800 m, but knowledge of their distribution is incomplete. *Lophelia prolifera* and *Enallopsammia profunda* are the primary framework builders (Cairns and Stanley 1983), with minor contributions by *Madrepora carolina* and *Solenosmilia variabilis* (Cairns 1979). *Enallopsammia profunda* dominates the banks, while *L. prolifera* is typically limited to upper portions (Stetson et al. 1962). In some places, these fragile, branching corals coalesce to form dense thickets; in other areas, they produce isolated ridges and mounds of their own debris.

Coral growth on the deepwater banks is relatively slow, 5 to 7 mm/year (Wilson 1979). Several environmental characteristics seem necessary for these banks to develop,

including hard substrata, vigorous currents, and temperatures ranging from 5 to 10°C (Cairns and Stanley 1983). Habitat depths indicate dependence upon planktonic and detrital food sources. Because these reefs are so inaccessible, little else is known of their ecology.

The banks serve as refuge, feeding, and breeding grounds, as well as nursery shelters for other species. Large, commercially exploited deep-sea crabs (*Geryon quinquedens* and *G. fenneri*) are found associated with deepwater coral banks in the Gulf of Mexico and off Southeast Florida (Neumann and Ball 1970). Corals provide both food and shelter for fish (Squires 1964). Isopods and other crustaceans are also associated with these banks. Other publications that deal with Florida deep coral banks include Teichert (1958), Moore and Bullis (1960), and Neumann et al. (1977).

Interactions of Coral Reef Biota with Associated Communities

Coral reefs are interdependent with other marine and terrestrial communities that constitute the coastal ecosystem. Energy, chemical constituents, and mobile species move between the reefs and other communities, including pelagic, mangrove, seagrass, sedimentary, and hardground. This interdependence is exemplified by the life cycle of the spiny lobster (*Panulirus argus*) in the Florida Keys. Mature spiny lobsters live, breed, and spawn on coral reefs. The planktonic larvae live for several months in the oceanic water column. Juveniles settle near shore in *Laurencia* algae associated with seagrass communities (Marx and Herrnkind 1985). Larger juveniles live in live bottom habitats or mangroves before moving offshore to patch reefs and finally to reef margins as mature adults (Lyons et al. 1981). Adult lobsters also use different ecosystem components on a diurnal cycle, seeking refuge in reef dens during the day and moving into seagrass beds and sedimentary environments to forage for small molluscs, crustaceans, and other prey at night.

Understanding that coral reefs are adapted to nutrient-deficient waters (Muscatine and Porter 1977; Smith et al. 1981; Hallock and Schlager 1986) helps explain why reefs near terrestrial nutrient sources are so dependent upon associated ecosystems, particularly mangroves and seagrasses (Jaap and Hallock in press). Nutrients and sediments shed from terrestrial environments are intercepted by mangrove and seagrass communities, protecting the reef margin from their detrimental effects. With their more plentiful supplies of nutrients, mangrove and seagrass communities also provide nursery areas for juveniles, and foraging areas for adult animals that inhabit the reef.

Environmental Phenomena

In general, natural environmental stresses on coral reefs include extreme temperature fluctuations and hurricanes and other storms that produce high volumes of terrestrial runoff of low salinity and high-sediment load. Most of Florida's reefs are sufficiently distant from the relatively small keys that salinity and sedimentation generally do not produce serious environmental stress.

Because South Florida occurs in the transition between temperate and subtropical climatic zones, the Florida Keys are frequently exposed to winter, polar frontal systems that drastically cool the water (Walker 1981; Roberts et al. 1982). Thermal tolerance is species specific (Mayer 1914); however, most species display adverse affects below 15°C. Fish kills, coral bleaching, and mortality are often associated with hypothermic meteorological phenomena (Hudson et al. 1976; Jaap et al. 1989). Reefs adjacent to channels connecting the Atlantic to Florida Bay and at Dry Tortugas are more susceptible to this stress. Reefs offshore the northern Keys are closer to the Florida Current and are protected by the warmer waters.

Massive coral bleaching events (zooxanthellae expulsions) occur once or twice a decade; bleachings occurred during 1973, 1983, and 1987 (Jaap 1979, 1985, 1988). The cause in South Florida is believed to be hyperthermia brought on by long-lasting doldrums during late summer (Jaap 1985), in conjunction with El Nino - Southern Oscillation (ENSO) meteorology (Glynn 1988). Bleached Florida reefs usually recover in six to eight weeks following cessation of the doldrum. However, when the weather pattern continues for six weeks or longer, corals may not regain their color for several months. Rejuvenation is accomplished by cell division in remnant populations of zooxanthellae that remain in the coral tissues. Bleached corals have low tissue biomass, tissue carbon, and tissue nitrogen; reproduction (oocyte development) was disrupted in severely bleached specimens (Gassman and Szmant 1989). Weakened corals may be prone to algal overgrowth or disease (Shinn 1988).

Hurricanes play a significant role in coral reef development in the western Atlantic (Stoddard 1962, 1969; Woodley et al. 1981). The Florida Keys have a greater probability of hurricane impact than any other Florida coastal area (Florida Department of Natural Resources 1974). Violent hurricanes pass through the reef system (Sugg et al. 1970; Jindrich 1972; Shinn 1976), dislodging and fragmenting corals, moving fish away from their resident reefs, scouring and abrading the sessile organisms with sediments, and significantly reducing water transparency (Springer and McErlean 1962a; Ball et al. 1967; Shinn 1976). After Hurricane *Donna* in 1960 redistributed much of the coral at Grecian Rocks and Key Largo Dry Rocks, recovery took about 5 to 10 years (Shinn 1976). Such recovery indicates the resilience of a reef to mechanical destruction (Shinn 1988), although recovery depends on the scale of destruction.

Review of Human Interaction with Coral Reef Communities

As the human population has increased in South Florida and the Florida Keys, coral reefs of the Florida Reef Tract have suffered. Coral reefs are adapted to environments where nutrients are scarce and terrigenous sediment influx is limited; human activities inevitably increase inputs of both into nearshore waters. Clearing forest and mangroves, dredging, and boat operations all increase sedimentation stress. They also indirectly increase nutrient loading by reducing natural nutrient traps, including vegetation and soils, and by mixing nutrients into the water column that would otherwise be trapped in sediments. A workshop on coral reef research and management in the Florida Keys, held in Key Largo in June 1988 (Miller 1988), concluded that "The Florida Reef Tract is in serious trouble" and the first problem listed is "excessive nutrients and other waste products in the water originating from nearby land masses and Florida Bay" (Miller 1988). Lapointe and O'Connell (1988) demonstrated that the use of septic tanks and shallow injection wells in the porous limestones of the Florida Keys is accelerating eutrophication of surface waters. Mean concentrations of ammonium and nitrate were 350-fold higher in groundwaters of developed Keys as compared with pristine groundwaters; phosphate was 60-fold higher in groundwaters of developed Keys. During summer months, there is a greatly increased discharge of contaminated groundwater into sea-surface waters, raising nutrient concentrations and increasing phytoplankton stocks.

Terrestrial vegetation and mangroves are crucial to the survival of seagrass and coral reef communities because they act as filters, absorbing runoff, which carries sediments, organic debris, and nutrients, before it reaches the seagrass beds and reefs. Coastal urbanization threatens seagrass and reef habitats by removing these natural filters. At the same time, urban activities such as landscaping, dredging, and domestic waste disposal increase the need for the filters. Turbidity caused by sediments and plankton blooms reduces the depths to which seagrass and coral reefs can live. Eutrophication also stimulates benthic algal growth (which can prevent recruitment of larval corals) and increases microbial use of oxygen, reducing its availability in the environment. To the north, beach renourishment to counter erosion on the barrier islands of Dade, Broward,

and Palm Beach Counties has damaged reefs. Increased sedimentation rates, burial, and physical damage by dredge cables and anchors have all occurred there (Courtenay et al. 1974; Jaap 1984; Goldberg et al. 1985; Blair and Flynn 1988).

Although specific studies of the effects of excess nutrients on Florida's coral reefs have not yet been carried out, other research has shown how sensitive reef growth is to nutrient loading. Successful coral recruitment is inversely correlated with nutrient availability (Birkeland 1977). Smith et al. (1981) found that strong eutrophication can eliminate corals from a benthic community. Although mild eutrophication does not eliminate adult corals, an event such as excessive storm runoff can kill them, leaving the habitat to be taken over by benthic algae due to sparse juvenile coral recruitment. Tomascik and Sander (1985) found that coral growth was inversely proportional to particulate organic carbon concentrations in waters over the reefs of Barbados. Birkeland (1987) classified the coral reefs of the western Atlantic and Caribbean as "continental" because nutrients are readily available from nearby land sources. Hallock et al. (1988) observed nutrient suppression of coral reef development in an area remote from anthropogenic influence (the Nicaraguan Rise of the western Caribbean). Because the Florida Reef Tract is on the climatic boundary of reef development and is occasionally stressed by exceptionally strong winter cold fronts, Florida reefs can only survive if human activities that directly or indirectly affect coral reef communities are minimized.

Value of Florida Coral Reef Communities

Florida's reef system is a unique resource in the continental U.S. Coral reefs are vital to Florida's economy. Commercial and recreational fishing industries depend on numerous species that inhabit reefs during all or parts of their life cycles. Additionally, non-consumptive uses, such as boating, scuba diving, snorkeling, and educational and natural history activities, are major producers of local revenue. Considering lodging, meals, transportation, equipment rental, and boat charters, there are strong economic incentives for effective reef management and preservation involving the sustained vitality of the commercial and recreational fishing and diving industries. These industries contribute not only to Florida's economy but also to the quality of life for Florida residents and visitors. The very existence of the Florida Keys is the result of millions of years of coral and algal limestone deposition. The reefs serve as living breakwaters, dissipating storm and hurricane wave energies before they reach the coast, protecting low-elevation human settlements. The importance of Florida's shallow-water reefs as offshore breakwaters is often taken for granted. Sea level is rising several centimeters per decade (Scholl et al. 1969); healthy coral reefs can build at that rate and thus continue to function as self-tending breakwaters. However, pollution not only kills most corals but also increases the rate of bioerosion of reef framework (e.g., Smith et al. 1981; Hallock 1988), compounding the problem of rising sea level.

Finally, there is the ethical responsibility of society to conserve unique natural resources for future generations. From an ecological perspective, rational management must seek to maintain the organic evolutionary process that is responsible for the diversity of life found in the biosphere (Bradbury and Reichelt 1981). The U.S. has only one Florida Reef Tract and one Everglades. Society has the responsibility to preserve them.

Coral Reef Management

Several government agencies are responsible for specific areas of reef management. The State boundary is 5.6 km (3 nmi) seaward of the coast on the Atlantic (Ocean) side and 16.7 km (9 nmi) on the Gulf (Bay) side, except around islands and bays where there are special considerations. The area between the State boundary to the 370 km (200 nmi) National conservation boundary is under Federal jurisdiction. Thus, most patch reefs in the Upper Keys are under State jurisdiction, whereas bank reefs are under

Federal administration. In the Lower Keys off Key West, the islets of Sand Key and Pelican Shoal extend State jurisdiction to the outer bank reefs from Maryland Shoal to Satan Shoal. This complexity of boundaries makes enforcement difficult. The State of Florida and the Federal government have statutes protecting stony corals and the sea fan *Gorgonia* from harvest, sale, or damage on the seafloor. Permits from the Florida Department of Natural Resources (State waters) or the National Marine Fisheries Service (Federal zone) are required for all coral collections. Parks, sanctuaries, and National monuments receive special management. Fragmentation of responsibility makes it very difficult for an agency to react quickly to information on destructive human activities.

As previously noted, many vessels have grounded on Florida reefs. Such impacts not only damage or destroy the vessels, but also damage reef, seagrass, and mangrove habitats. Coral reef communities require at least several decades to recover from major natural disturbances; recovery following human disturbance is less predictable, especially if the habitat has been permanently altered (Pearson 1981). Large vessels, such as the freighter *Wellwood* which grounded in August 1984, devastate extensive areas of the reef (Gittings 1988; Hanisak et al. 1988; Hudson and Diaz, 1989). Large ships are a menace to Florida's coral reefs. In a span of 18 days three large ships ran aground on reefs off the Florida Keys during 1989. All of these accidents were caused by human error. The 47-m-long offshore oil supply vessel *Alec Owen Maitland* grounded on south Carysfort Reef on 25 October. The 145-m-long bulk carrier *Mavro Vetranic* grounded on Pulaski Shoal, Dry Tortugas on 30 October. The 143-m-long bulk carrier *Elpsis* grounded on a reef in the Key Largo National Marine Sanctuary on 11 November. It is difficult to understand these accidents; none occurred during severe weather conditions and none of the ships reported mechanical difficulties. All of these accidents caused massive damage to the coral reefs where the ships had grounded. Even small boats can drive antifouling paint or fiberglass into coral surfaces, cut deep gashes into coral heads, shatter stands of elkhorn coral, or split large head corals that are hundreds of years old. In addition to overt physical damage, these accidents seem to make corals more susceptible to disease. The large number of boats operating in waters around the Florida Keys results in numerous groundings every year. Most are caused by navigational errors or poor knowledge of local water hazards. Shallow patch reefs, such as Mosquito Bank off Key Largo, are particularly prone to damage by pleasure boats; boaters seeking shortcuts to offshore reefs commonly run aground on the patch reefs. Anchors (Halas 1985) and lobster and fish traps, when deployed on a reef, can crush and scar corals and other biota. Even during coral recovery, traps may be pulled across the reef until they clear the bottom, often abrading or dislodging algae, corals, and sponges.

Conclusions

While the majority of the continental U.S. lies in the temperate climatic zone, the Florida Keys border the subtropics. The Florida Keys possess a unique coastal ecosystem that is Caribbean-West Indian in its biogeographic affinity. This ecosystem is characterized by an onshore-to-offshore gradient of communities: a mangrove coastal fringe, and a mosaic of seagrass, sedimentary, and coral reef communities seaward of the coast. The coral reefs are a National heritage of an aesthetic value equal to the Grand Canyon or Yellowstone National Park. Nowhere else in the continental U.S. can a citizen experience coral formations, schools of tropical fish, and the bountiful variety of life found on a coral reef.

Coral reefs provide complex three-dimensional structure on an otherwise featureless continental shelf. The heterogeneity provides habitat that is occupied by many sessile and mobile species. These reefs are analogous to the tropical rain forest in ecological characteristics: high gross primary productivity, low net primary productivity, rapid recycling of limited chemical resources, extreme spatial complexity, high species diversity, and species interdependence (symbiosis).

The Florida Keys are economically dependent on the coastal ecosystem that includes coral reefs. The subtropical climate and clear, warm, azure waters provide an ambience that attracts millions of visitors from all over the world. Tourists come to snorkel, scuba dive, and view the reefs from glass-bottom boats. Reef-related recreational fishing and pleasure boating also support the economy of Monroe County. Commercial fishing, which includes the harvest of spiny lobster, grouper, and snapper from coral reef habitat, is second only to tourism in economic importance. Much of this harvest is consumed by the tourists in local restaurants. Coral reefs are a refuge and breeding habitat for lobster, grouper, and snapper, which are being utilized at or near maximum sustainable yield.

Unfortunately, the geographic setting of Florida's reefs exposes them to less-than-optimal environmental conditions. Because they are among the northernmost coral reefs in the Caribbean/western Atlantic, extreme winter cold fronts periodically stress the reefs, causing fish and coral kills. Summer doldrums that create abnormally warm water also stress the reefs, as do frequent hurricanes.

In addition to natural stresses, urbanization of the Florida Keys and increased tourism have reduced coral reef vitality. During the last decade, environmental quality in the Florida Keys has deteriorated. Problems include declining water quality (due to nutrient enrichment and turbidity); boat and ship groundings; loss of coastal mangroves, which serve as a natural buffer-filter between inhabited areas and the more sensitive seagrasses and reefs; contamination of the habitat by pesticides and trace metals; and physical damage by anchors, divers, and fishing gear. The synergistic effect of these human actions threatens the continued survival of these sensitive marine communities.

The possibility of a major oil spill from existing tanker traffic or future oil exploration and development is further cause for concern. The Bahia las Minas spill in Panama, which occurred in a similar environmental setting, caused significant, long-term damage to coastal communities (see **Chapter 15**). Because South Florida coral reefs are precariously located near the ecological limits for reef growth, their ability to recover from such damage is doubtful.

From an ecological viewpoint, the diversity observed in the Florida Keys coral reef ecosystem has evolved through natural selection with little or no human interference. If this process is to continue, human effects on the reefs must be minimized, or a unique and precious National heritage will be lost.

There are numerous ongoing research programs in the Florida Keys area, including programs sponsored by the National Oceanic and Atmospheric Administration, the National Park Service, the U.S. Geological Survey, the State of Florida, private foundations, and others. Some critical research needs are outlined below.

In general, details of biology and life history are poorly known for the vast majority of coral reef biota. Population dynamics and interspecific interactions among reef organisms must be more thoroughly investigated. In particular, because diseases and algal overgrowth are rapidly eliminating living corals in the Florida Keys (e.g., Shinn et al. 1989; Porter unpubl. data as reported in Miller 1988 and Shinn 1988), research is immediately needed on pathogens of coral and other reef organisms. The extent of coral pathogen distribution in the Reef Tract should be studied. Information is needed on the types of pathogenic conditions present and the net annual loss of coral cover due to disease. Further research is also needed on coral-algal and coral-bioeroder interactions. Because growth of algae, bioeroders, and possibly disease pathogens seem to be promoted by nutrient loading, research must include determining sources of anthropogenic nutrients and determining ways to reduce nutrient loading. In addition to nutrient

loading by sewage outfalls and septic tanks in the Keys, deterioration of the water quality of Florida Bay must be assessed and reversed. This will require integrated studies of the entire South Florida assemblage of ecosystems.

The level and impact of human usage of the Reef Tract needs to be studied. Information is needed on the number of users, the resources they are utilizing, the effects they are having on water quality, and the amount of physical damage to reef resources that is attributable to human activities.

As the result of growing scientific and public concern for the deteriorating health of the Florida Reef Tract, the Florida Keys Coral Reef Research and Management Workshop was convened in June 1988, bringing together over 50 experts on coral reefs and their management. The recommendations and conclusions of that workshop (Miller 1988) are summarized below:

"A. The Florida Reef Tract is in serious trouble because of a combination of events including:

1. Excessive nutrients and other waste products in the water originating from nearby land masses and Florida Bay.
2. Physical damage to corals caused by boaters, divers, and fishermen.
3. Natural causes such as storms, thermal shock from cold water in periodic storm events, warm water events....
4. The lack of consistent management policies....
5. The lack of sufficient data to make effective long range management decisions.
6. Insufficient education of the public....

B. A series of definitive steps can be taken now to reduce the rate of deterioration of the Florida Reef Tract and to aid in its recovery.

1. Establish permanent monitoring sites....
2. Initiate the following research studies, using standardized instrumentation, at each of the permanent monitoring sites:
   (a) animal and plant inventories
   (b) nutrient transport and loading
   (c) installation of oceanographic 'weather' stations
   (d) satellite, aerial, and underwater photography
   (e) coral physiology, population dynamics, and biotic processes.
3. Initiate a series of education and management programs aimed at immediately reducing the adverse human impact on reefs...."

There are initiatives at the Federal and State level to designate the Florida Reef Tract as a National Marine Sanctuary and to designate a shipping avoidance zone offshore of the Florida Keys. These efforts, should they succeed, will provide significantly improved management of reef resources. However, the threat of urbanization and nutrient runoff from uplands would not be addressed by these management programs. The reef system must be managed in the context of the drainage basin patterns and the anthropogenic processes that threaten environmental quality.

SEAGRASS BEDS

Joseph C. Zieman

Introduction

Seagrass ecosystems are among the richest, most productive, and most important of all coastal systems (Westlake 1963; Wood et al. 1969; Odum et al. 1973; Zieman 1982). Structurally, seagrass ecosystems are simultaneously simple and complex. The extensive undersea meadows stretching for hundreds of kilometers may be composed of only one to perhaps four species of seagrasses, so that only a few species literally define the system. At the same time, the community is extremely complex because of the hundreds to thousands of species of associated flora and fauna that inhabit seagrass meadows and utilize the food, substrate, and shelter provided by the plants.

Florida has two major regions of inshore (<15 m depth) seagrass meadows and many other smaller inshore beds that reach very high densities. Recent studies have shown that there are extensive offshore seagrass beds in deeper water (Continental Shelf Associates, Inc. and Martel Laboratories, Inc. 1985; Continental Shelf Associates, Inc. 1989). Although the extent of these sparse offshore beds has been mapped, their overall ecological importance is unknown.

This section reviews aspects of the ecology of the seagrass ecosystems of South Florida. For other extensive reviews of these systems, see the monographs or articles by Phillips (1960a), Zieman (1982, 1987), and Zieman and Zieman (1989). Two important journal sources are the *Proceedings of the Florida Bay Symposium* (*Bull. Mar. Sci.* 44:1) and the *Proceedings of the Symposium on Subtropical-Tropical Seagrasses of the Southeastern United States* (Durako et al. 1987).

Functions of Seagrass Ecosystems

Wood et al. (1969) published the first classification of the common properties and processes provided by seagrass beds. The following is an updated version of the earlier classification scheme taken from Zieman (1982). Seagrass ecosystems have the following properties:

- **High Production and Growth**. The ability of seagrasses to exert a major influence on the marine seascape is due in large part to their extremely rapid growth and high net productivity.

- **Food and Feeding Pathways**. Photosynthetically fixed energy from the seagrasses may follow either of two general pathways: direct grazing of organisms on living plant material or utilization of detritus from decaying seagrass material, primarily leaves. Export of seagrass material, both living and detrital, away from a seagrass bed allows for further distribution of energy remote from its original source.

- **Shelter**. Seagrass beds serve as a nursery ground, that is, a place of both food and shelter, for juveniles of a variety of finfish and shellfish of commercial, sport-fishing, and ecological importance.

- **Habitat Stabilization**. Seagrasses stabilize sediments in two ways: (1) the leaves reduce water velocity near the sediment-water interface, promoting sedimentation of particles as well as inhibiting resuspension; and (2) roots and rhizomes form a complex, interlocking matrix which binds sediments and retards erosion.

- Nutrient Effects. Production of seagrass detritus provides organic matter for sedimentary nutrient recycling. Epiphytic algae and plant-associated microbes fix nitrogen, thus adding to the surrounding nutrient pool. In addition, seagrasses can translocate nutrients from sediments to the water column through the leaves.

Direct herbivory on green seagrass leaves is confined to a small number of species, and is most prevalent in tropical and subtropical regions, especially in the vicinity of coral reefs. Since the time of Petersen (1918), the detrital food web has been considered the main trophic pathway in seagrass meadows, and current studies continue to support this concept, although direct herbivory can be locally important in some areas (Thayer et al. 1984; Zieman et al. 1984a). Many beds, especially those dominated by *Syringodium*, export large quantities of organic material to other distant ecosystems either by surface drift or benthic transport.

In subtropical waters of South Florida, seagrass meadows often bridge large areas between mangrove and coral reef communities, while also serving as primary nursery and feeding grounds themselves (Zieman 1982). On the west coast of Florida, they function in a similar manner as nursery and feeding grounds, but here serve as an interface between the coastal salt marsh communities and offshore habitats of the eastern Gulf of Mexico (Lewis et al. 1985b).

Seagrasses of South Florida

Seagrasses are a small group of monocotyledonous plants that live completely submerged in the marine environment. It is important to recognize seagrass species, as they possess quite different habitat values largely due to their differing morphologies, biomass, and productivity. The small number of species occurring in these waters, and their distinctive gross morphologies, preclude the need for a dichotomous key, although systematic works such as den Hartog (1970) and Tomlinson (1980) are available for comparison with seagrasses from other areas. Illustrations and more detailed descriptions are found in Phillips (1960a), Zieman (1982), and Zieman and Zieman (1989).

The three dominant species in South Florida waters are *Thalassia testudinum*, *Syringodium filiforme*, and *Halodule wrightii*.

Thalassia testudinum, turtle grass, is the largest and most robust of the South Florida seagrasses, and the most abundant throughout the study area (Iverson and Bittaker 1986; Zieman et al. 1988). It possesses large, strap-like leaves and has an extensive root and rhizome system used for anchorage, nutrient uptake, and storage. It produces the highest biomass and has the greatest areal productivity.

Syringodium filiforme, manatee grass, is distinctive in having cylindrical leaves that are quite brittle and buoyant. These float readily, and when broken off, are easily transported by winds and currents. In the study area, it is most common on the outer fringes of Florida Bay in deep tidal channels and in back reef areas. It is not common in calm bays or in areas with lowered salinity.

Halodule wrightii, shoal grass, has narrow leaves and a shallow root system. It is recognized as the pioneer species in the successional development of seagrass beds in the Gulf and Caribbean, and can colonize disturbed areas rapidly. As its common name indicates, it is often found in shallow waters on banks or immediately adjacent to mangrove islands where it may be subjected to repeated exposure to the atmosphere.

Ruppia maritima, widgeon or ditch grass, is a euryhaline angiosperm found abundantly in fresh water. In the marine environment, it grows primarily in low salinity areas, but is locally abundant in parts of Florida Bay where salinity reaches 60 ppt.

Three species of *Halophila* occur in South Florida: *H. decipiens*, *H. engelmannii*, and *H. johnsonii*. These are small plants, growing only a few centimeters high. Although they cover large areas offshore, they never reach significant densities compared with the biomass of other seagrass species. With only slight changes in the regional species of *Halophila*, this species grouping is found throughout the Caribbean and South Atlantic.

Functional Morphology and Mode of Growth

Although differences exist, seagrasses show common structure and growth patterns (den Hartog 1970; Zieman and Wetzel 1980). *Thalassia* serves as a local model. On a *Thalassia* short shoot, which typically has two to five leaves at a time, new leaves grow on alternating sides of a central meristem that is enclosed by old leaf sheaths. New growth on leaves is produced by the basal meristem.

Thalassia rhizomes occur from 1 to 25 cm below the sediment surface, but are typically found in the depth range of 3 to 10 cm. The rhizomes of *Halodule* and *Halophila* are near the surface and often exposed. While *Syringodium* rhizomes generally occur at an intermediate depth, in strong currents they may be exposed, even extending up into the water column. Roots of *Thalassia* emerge from the rhizomes and the short shoots. The roots are much smaller in cross section than rhizomes, and vary in length according to sediment composition and depth.

Leaf width can reflect morphogeographic variation (McMillan 1978; McMillan and Phillips 1979). While studying *Thalassia* seedlings on a latitudinal stress gradient in Florida, Durako and Moffler (1981) found that the greatest leaf widths occurred in the Keys and the narrowest leaf widths occurred in North Florida. In addition, leaf morphologies showed sexual differences, with female short shoots tending to have narrower leaves than male shoots (Durako and Moffler 1985a).

Reproduction

Seagrasses, capable of forming vast meadows with high areal productivity, seem to reproduce primarily by vegetative growth; however, sexual reproduction is important in providing the genetic plasticity necessary for successful adaptation and competition. Many extensive seagrass beds have never been found to reproduce sexually and are believed to be large clones of a single plant (McMillan 1982). All species reproduce sexually. It is believed that *Halodule*, *Syringodium*, and *Thalassia* are dioecious, *Ruppia* is monoecious, and *Halophila* is mixed (Moffler and Durako 1987).

Halodule produces fruit at the rhizome level. The fruit may reside dormant in sediments for at least 46 months, providing a seed reservoir that may be exploited following a major disturbance (McMillan 1981). *Syringodium* flowering and seeding is highly variable. The seeds, which are produced above the sediments and can be widely distributed, can have a dormancy of at least three years (McMillan 1981, 1983). *Thalassia* produces flowers and fruits at the sediment surface. The fruits are buoyant, and float until they split and release the seeds. Reproduction in this plant has been well studied, but is far from well understood. Flower production in Florida populations of *Thalassia* occurs from April to August or September, peaking in June (Orpurt and Boral 1964; Grey and Moffler 1978; Durako and Moffler 1985b). Spatial density distributions showed that higher numbers of female plants occurred on the fringes of the bed where short shoots are generally younger, while more male plants were found in the

center on presumably older short shoots. This pattern could reflect an age-related sexual expression in the plants, although environmental factors and clonal differences can also influence leaf width. Reproduction seems to be day-length neutral, requires higher salinities, and is synchronized by temperature (Moffler and Durako 1987). Seed production can vary greatly, even within a single bed, and the importance of seedling success in bed maintenance is unknown.

Distribution and its Control in Seagrass Ecosystems

Areal Extent

Seagrass beds are generally located in protected waters. This may be in island-fringed lagoons or estuaries, behind reefs, or behind barrier islands. A notable exception is the Big Bend area of the northwest coast of Florida, where unique physical conditions create one of the world's few zero-energy coastlines (Murali 1982). This meadow is 3,000 km^2 and is second in size only to the enormous area of beds in South Florida which include Florida Bay and the area of beds behind the Florida Reef Tract from just south of Key Biscayne to Key West, totaling 5,500 km^2 (Iverson and Bittaker 1986).

Seagrass distribution is controlled by three primary variables: light, sediment depth, and turbulence. Where there is sufficient light (generally translating to reduced turbidity), sufficient sediment depth, and waters protected from major storm waves, seagrasses can usually exist. Seagrasses are reduced or excluded where excess runoff and turbidity create unfavorable conditions such as off the Ten Thousand Islands and in Tampa Bay, but are present in most other estuaries. In deeper shelf waters, hurricanes have been found to disturb deep *Halophila* beds, although the beds recovered with time (Continental Shelf Associates, Inc. 1986).

Regional distribution is discussed in the Introduction to this chapter. General seagrass distribution in Florida is discussed by Zieman (1982), Iverson and Bittaker (1986), and Zieman and Zieman (1989). Offshore seagrass distributions are discussed by Continental Shelf Associates, Inc. and Martel Laboratories, Inc. (1985) and by Continental Shelf Associates, Inc. (1989).

Vertical Distribution

The development of rich, productive seagrass beds is confined to depths of 10 to 12 m or less, although seagrasses have been recorded from as deep as 42 m. In Florida Bay, maximum density occurs between 1 and 3 m, while in the clearer waters behind the Florida Reef Tract, dense beds exist at 6 to 8 m. Depth distribution is limited by exposure and desiccation in shallow areas, and light penetration at depth. The plants can tolerate brief aerial exposure, but lose extensive numbers of leaves if the exposure is prolonged or the conditions are extreme.

Halodule, and *Ruppia* if present, generally occur in the shallowest water, being more tolerant of exposure than the other species.

Thalassia is found in waters nearly as shallow as *Halodule*. Exposure of these flats on spring low tides commonly produces leaf mortality. Throughout depths of 1 to 10 m, all of the species may be found, singly or mixed; however, *Thalassia* is the unquestionable dominant in most areas, frequently forming extensive meadows that stretch for tens of kilometers. In South Florida, beds tend to be monospecific, whereas in the north-central part of the State, major beds are frequently multi-species mixes.

Seagrass density is sparse deeper than 10 to 12 m. *Syringodium* will frequently replace *Thalassia*, occurring down to about 15 m where it in turn is replaced by *Halodule*. As the major species reach their depth limits, fine carpets of *Halophila* occur to at least 40 m in depth. In the shallow but highly turbid waters off the Shark River in Southwest Florida, *Halophila* is sparse but widespread in occurrence. It has recently been found in waters as deep as 37 m off Southwest Florida (Continental Shelf Associates, Inc. 1989).

Syringodium is locally abundant in several types of areas in South Florida waters, being well adapted to both turbulence and rapid water flow. In highly turbulent waters immediately behind the Florida Reef Tract, *Syringodium* commonly occurs either in dense monospecific stands or intermixed with *Thalassia*. Throughout the Florida Keys, *Syringodium* also commonly exists in dense stands in deep channels with strong currents and high turbidity.

Numerous studies in Florida have illustrated the general pattern of vertical zonation in seagrass beds described above (Phillips 1960a; Strawn 1961; Zieman 1982; Lewis et al. 1985a; Zieman and Zieman 1989), although localized conditions create much variability. The depths given represent those found in very clear waters. In turbid water areas, the same pattern would be expected, but the ranges of the various species would be attenuated. A vertical zonation gradient that extends to 10 or 15 m in the Keys or Dry Tortugas will be compressed to 2 m or even less in highly turbid estuaries such as Tampa Bay or northern Biscayne Bay, or even in certain basins in Florida Bay free of human impact.

Limiting Variables and Tolerances

Physical Variables

Temperature. Being tropical and subtropical plants, the local seagrasses are particularly susceptible to low temperatures. *Thalassia* in Biscayne Bay showed maximum production at 28 to 30 °C (**Figure 4.5**). In Anclote Estuary north of Tampa Bay, Barber and Behrens (1985) found that maximal growth of *Syringodium* occurred between 23 and 29 °C and between 23 and 31 °C for *Thalassia*. In this power plant study, stations having thermal impact had higher productivity than non-impacted areas, but *Syringodium* productivity was depressed at the warmer stations. Seagrasses from North Florida are most tolerant of low temperatures; those of the Florida Keys are least tolerant (McMillan 1979). Seedlings grown in culture maintained this pattern of tolerance for 22 months.

Salinity. South Florida seagrasses have a salinity optimum near that of oceanic water, but are generally able to tolerate wide fluctuations in salinity (**Figure 4.5**). Salinity tolerances among species coincide with thermal tolerances: *Ruppia* is the most euryhaline, followed by *Halodule*, *Thalassia*, and *Syringodium*. *Halophila* is the least euryhaline of the seagrasses.

Thalassia has an optimum salinity ranging from 24 to 35 ppt (Phillips 1960a; McMillan and Moseley 1967; Zieman 1975a). It can survive short periods of exposure to extremes ranging from 3.5 ppt (Sculthorpe 1967) to 60 ppt (McMillan and Mosely 1967). Significant leaf loss frequently follows exposure to low salinity extremes. Recently, a deliberate release of fresh water into Manatee Bay and Barnes Sound caused massive defoliation of the seagrasses. Whether these were killed or will recover remains to be seen (M. Robblee, pers. comm. 1988, Everglades National Park). The effect of freshwater runoff following a hurricane was considered more damaging to seagrasses than the effects of high winds and tidal surge (Thomas et al. 1961). Short-term freshwater releases often cause massive defoliation, but do not kill the rhizomes, and the plants can recover if the stress is removed.

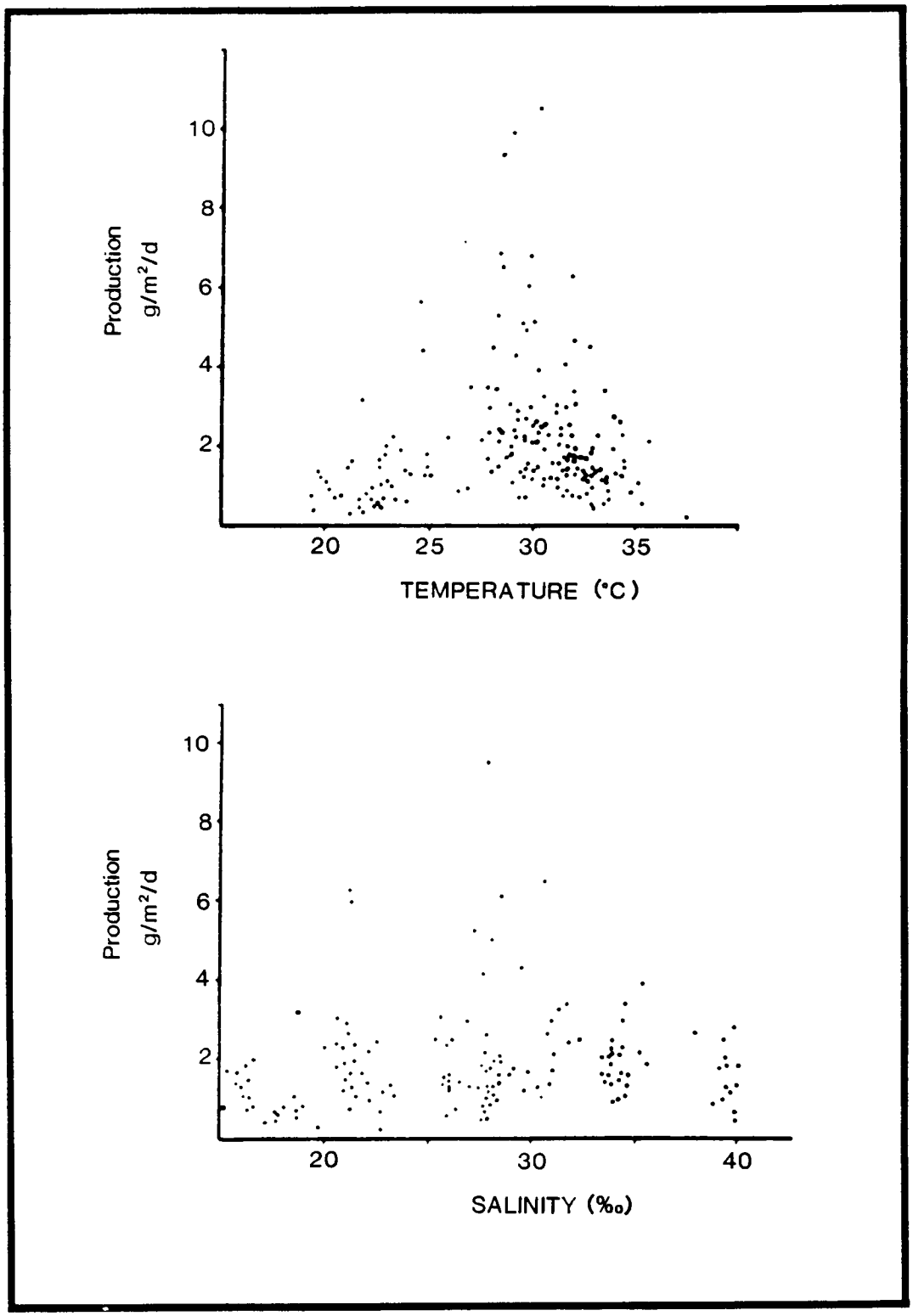


Figure 4.5. Temperature and salinity responses of *Thalassia* in Biscayne Bay (From: Zieman 1975a).

Halodule does not tolerate salinities <3.5 ppt (McMahan 1968). *Ruppia maritima* grows primarily in brackish water (Verhoeven 1975) and was observed growing near river mouths in Everglades National Park as well as in salinities up to 58 ppt (J. Zieman, pers. observ.). *Ruppia* has been observed to 10 m in depth 18 km (10 nmi) offshore in North Florida, in areas where salinities were quite low due to offshore freshwater springs (Earle 1972). *Halophila engelmannii* occurs off the mouth of the Econfina River, an area of relatively low salinity (Zimmerman and Livingston 1976). Recent studies in Florida Bay determined that *Thalassia*, *Syringodium*, *Halodule*, and *Ruppia* all grow successfully to at least 58 ppt for protracted periods (J. Zieman; M. Robblee; J. Fourqurean, Univ. of Virginia, pers. observ. 1989).

Light. The fact that well-developed seagrass beds do not occur at depths >10 m in the Caribbean has been considered indirect evidence that photosynthesis in seagrasses requires high light intensity, and that light penetration limits the depth to which seagrasses can grow (Humm 1956; Buesa 1975; Wiginton and McMillan 1979). *Thalassia* appears to be limited to depths where 10% of sea surface light energy penetrates. Depths calculated for Northwest Florida were 7 m for the part of the seagrass bed between Tarpon Springs and Crystal River, and 4.5 m for the portion north of Crystal River; depths approximated the deeper seaward limit of the major seagrass beds in the eastern Gulf of Mexico, except for the deeper *Halophila* beds (R. L. Iverson, pers. comm. 1988, Florida State Univ.). Although *Thalassia* and *Syringodium* occurred at greater depths in Cuban coastal waters (Buesa 1974) and in St. Croix waters (Wiginton and McMillan 1979) than in the Big Bend area and Florida Bay, most leaf biomass in the northwestern Cuba and St. Croix seagrass beds was located shallower than the depth to which 10% of surface light energy penetrated. Buesa (1975) reported the following depth maxima for seagrasses off the northwest coast of Cuba: *Thalassia*, 14 m; *Syringodium*, 16.5 m; *Halophila decipiens*, 24.3 m; and *Halophila engelmannii*, 14.4 m. However, maximum biomass for *Thalassia* was located between 1- to 3-m depths, whereas for *Syringodium* it was located between 12- to 14-m depths.

Although light quantity is being increasingly studied, little attention has been given to light quality as a determinant of production and distribution. Longer red wavelengths are absorbed in the first few meters in both clear and turbid waters. Clear tropical waters of the Caribbean Sea are enriched in blue light, while in turbid shallow waters, such as parts of Florida Bay and the Southwest Florida coast, enrichment of green wavelengths occurs. *Thalassia* responds best to red light (629 nm), which is the most rapidly attenuated, while *Syringodium* grows best with blue wavelengths (400 nm) (Buesa 1975). Wiginton and McMillan (1979) reported that chlorophyll *a* to chlorophyll *b* ratios increased with increasing depths, but they concluded that light quantity rather than quality was the primary environmental determinant of seagrass depth distribution.

Humm (1973) and Phillips (1960a) observed that *Ruppia* occurred in areas of low light and high turbidity. *Halophila engelmannii* also grows in shallow, turbid waters as well as in deeper, clearer waters (Zimmerman and Livingston 1976).

Oxygen. Dissolved oxygen within the water column of seagrass beds generally is adequate for the respiratory demands of the plants themselves and associated organisms. In *Thalassia* beds, photosynthetic oxygen production can be so high that bubbles escape from the leaf margins in late afternoon. Seagrasses are less susceptible to low oxygen concentrations than the animals of the grass beds; nevertheless, leaf mortality and increased microbial activity coincided with lowered oxygen levels in Japanese *Zostera* beds (Kikuchi 1980). Low oxygen levels slow the rate of respiration, and when internal oxygen concentrations are lowered, the plant's rate of respiration is controlled by diffusion of oxygen from the water column. If anoxia develops, the plants are forced to use anaerobic respiration, which is much less efficient and produces toxic products, stressing the plants.

Water Currents. Seagrass biomass and production are greatly influenced by current velocity. Maximum standing crops for both *Thalassia* and *Zostera* occurred where current velocities averaged 0.5 m/s (Conover 1968). It is believed that such velocities disrupt diffusion gradients and thus increase the availability of carbon dioxide and nutrients to the plants (Conover 1968). In South Florida, the densest stands of *Thalassia* and *Syringodium* occur in tidal channels separating mangrove islands where current speeds are high.

In seagrass meadows with persistent high-velocity currents, lunate-shaped erosional features called migrating blowouts are often created (Patriquin 1975). These features slowly migrate through the bed in the direction of the current (Zieman 1982). Recolonization takes place at the trailing edge of the blowout, and here the successional sequence of seagrass colonization can be observed.

Sediment. Seagrasses, being rooted plants, have a minimum sediment depth requirement which differs among the species. *Halodule*'s shallow surficial root system allows it to colonize thin sediments in areas of minimal hydraulic stability (Fonseca et al. 1981). *Thalassia*'s more massive root and rhizome mat requires up to 50 cm of sediment for lush plant growth, although it occurs in shallower sediments (**Figure 4.6**). Seagrasses occur in a variety of substrates, from fine muds to coarse sands. In Tampa Bay, Phillips (1962) observed that seagrasses grew only in muddy sand substrates, while patches of pure sand were unvegetated.

Reducing sediments seem to always be associated with well-developed *Thalassia testudinum* beds. This most likely reflects the greater importance of sediment nutrient content and microbial nutrient recycling in meadows of this species, rather than a specific requirement for reducing conditions. It was traditionally thought that *Halodule* grows in more aerobic substrates; however, Pulich (1985), working in Texas waters, postulated that *Ruppia* normally occurs in low-nutrient sediments while *Halodule* prefers organic-rich sediments where sulfate reduction is substantial. The distribution of *Syringodium filiforme* is possibly less dependent on sediment type, and this species exists in both oxidized and reduced sediments (Patriquin and Knowles 1972). *Ruppia* generally occurs in finer substrates than the above species (Phillips 1960a), while *Halophila* grows in a wide range of substrates, from muddy sands to limestone, and even on mangrove roots (Earle 1972).

Exposure. *Thalassia* and *Syringodium* are subtidal plants and do not tolerate prolonged exposure; however, *Thalassia* does grow on flats where periodic exposure causes leaf kill and defoliation. *Halodule* can withstand repeated exposure at low tide, and is most abundant between neap low and spring low tide marks in higher salinities (Phillips 1960a). In low-salinity intertidal areas, *Ruppia* and *Halodule* often occur in mixed stands (Phillips 1962; Earle 1972). Dawes (1987) noted that *Ruppia* forms extensive meadows on flats where it can be exposed to intense sun, and appears to tolerate some desiccation.

Biogeochemistry of Seagrass Meadows: Nutrient Supply and Cycling

As seagrasses derive most of their nutrients from their root system, the microbially mediated chemical processes in marine sediments provide the main source of nutrients for seagrass growth (Capone and Taylor 1980). Although seagrasses require a variety of macronutrients and micronutrients for nutrition, most research has been directed to the source and rate of supply of nitrogen which, along with phosphorus, is a major limiting factor. Organic nitrogen sources to the sediments include dead plant material (litter and buried roots and rhizomes), dead animal material, and excretory products and exudates of living plants and animals. Bacterial processes convert organic nitrogen compounds to ammonia, primarily in anoxic sediments which usually exist only a few millimeters beneath the sediment surface. Ammonia that is not rapidly bound by these

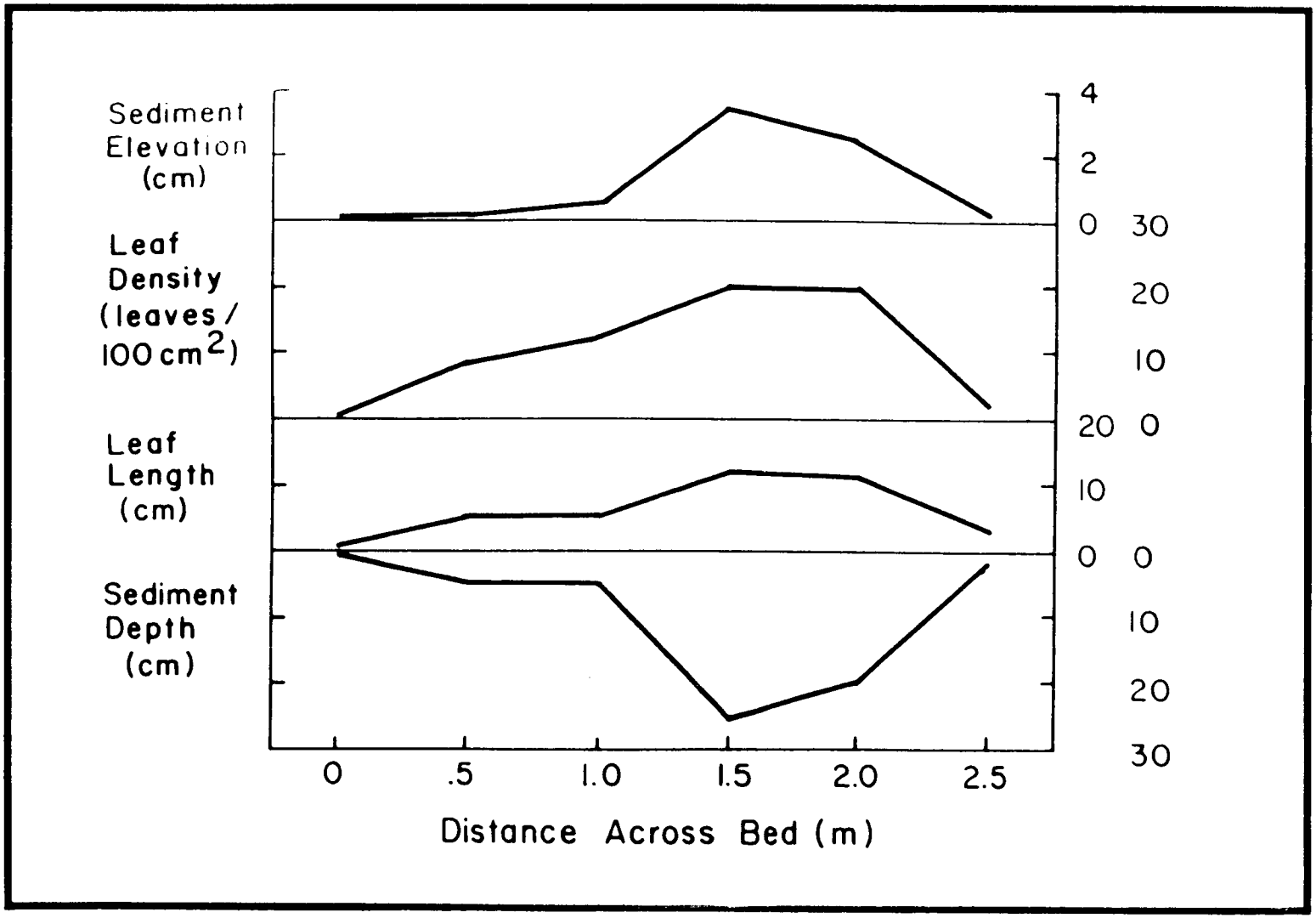


Figure 4.6. Seagrass meadow development as a function of sediment depth (From: Zieman 1972). Note the denser and longer leaf canopy developed over the deeper sediments.

processes will diffuse upward to the aerobic zone where it can either escape to the water column or be converted to nitrate by nitrifying bacteria in the presence of oxygen. Nitrate is usually in very low abundance or absent in sediments, as it is either rapidly metabolized or converted to dinitrogen (N_2) via denitrifying bacteria.

Microbial nitrogen fixation can occur either in the rhizosphere or phyllosphere. Capone and Taylor (1980) agreed with Patriquin (1972) that the primary source of nitrogen for leaf production is recycled material from sediments, but found that rhizosphere fixation can supply 20 to 50% of the plant's requirements. Capone et al. (1979) concluded that nitrogen fixed in the phyllosphere contributed primarily to the epiphytic community, while fixation in the rhizosphere contributed mainly to macrophyte production. Fixation by epiphytes can contribute to seagrass nutrition directly, as demonstrated by transfers between leaf and epiphyte (Harlin 1971; McRoy and Goering 1974), and indirectly, because after the leaves senesce and detach, most of them decay and become part of the litter, some of which will be incorporated in the sediments.

Phosphorus is the other major macronutrient, and its cycling differs fundamentally from that of nitrogen. In normal biogeochemical cycling, phosphorus has no gaseous phase, does not change valence state, and ultimately has one primary source, the weathering of phosphate minerals. While phosphorus is in very low concentrations in tropical waters, it is often relatively abundant in sediments. Sediments of seagrass beds show increased levels when compared to sediments outside the beds (McRoy et al. 1972; Patriquin 1972). In Barbados, dissolved phosphate in pore waters of carbonate sediments were low and Patriquin (1972) concluded that the overlying waters were the primary source of phosphate to the seagrasses. Rosenfeld (1979) found that Florida Bay pore water concentrations were two orders of magnitude lower than pore water concentrations in Long Island Sound, and attributed the difference to the adsorption of phosphate by calcium carbonate. Rapid adsorption of phosphate occurs on calcite and aragonite (Berner and Morse 1974; Morse et al. 1979). Thus, it is likely that phosphate is more limiting than nitrogen to seagrasses in tropical carbonate sediments.

The role of microbes in controlling the availability of phosphate to seagrasses is unclear. While the plants take up only orthophosphate, bacteria can also directly incorporate or hydrolyze organic phosphates. In addition, some bacteria can produce organic acids which, by lowering the pH, can solubilize inorganic phosphates (Fenchel and Blackburn 1979). Rapid uptake and remineralization of phosphate by bacteria and their grazers can return phosphate to the inorganic pool.

In a shallow-water successional sequence leading to *Thalassia*, the early stages are often characterized by low sediment organic matter and exogenous nutrient supply; that is, the community relies on nutrients brought in from adjacent areas by water movement as opposed to *in situ* regeneration. With the succession from rhizophytic algae to *Thalassia*, there is progressive development in the below-ground biomass of the community as well as the portion exposed in the water column. With progressive increase in leaf area, sediment trapping and particle retention increase, adding organic matter to the sedimentary microbial cycles. Seagrasses in carbonate substrates with small external nutrient sources may often be nutrient limited. Powell et al. (1989) found that in eastern Florida Bay, nutrient additions from bird droppings could significantly increase seagrass biomass. Tissue content suggested that phosphorus was limiting in control areas and nitrogen became limiting in the vicinity of bird enrichment.

Available evidence suggests that seagrasses are extremely efficient at capturing and utilizing nutrients, and that this is a major factor in their ability to maintain high productivity in a relatively nutrient-poor environment.

Production Ecology

Biomass

Seagrass biomass can vary greatly depending not only on the species but on such environmental variables as available light, sediment depth, nutrient availability, temperature, and circulation. Dense stands of *Halodule* typically reach a biomass of several hundred grams per square meter; *Syringodium* reaches maximum development at 1,200 to 1,500 g dry wt/m^2; maximum reported values for *Thalassia* are over 7,000 g dry wt/m^2. Tables showing the diversity of values are provided in McRoy and McMillan (1977), Zieman (1982), Lewis et al. (1985b), and Zieman and Zieman (1989).

Most seagrass biomass, particularly in the large species, is below the sediment surface. Typically, 15 to 20% of *Thalassia*'s biomass is in the leaves, although reported values range from 10 to 45%, with the rest made up by roots, rhizomes, short shoots, and sheathing leaves (Zieman 1975a, 1982). Sediment texture can affect the relative amount of biomass above and below the surface: the ratio of leaf to root and rhizome biomass in *Thalassia* increased from 1:3 in fine mud, to 1:5 in mud, and 1:7 in coarse sand (Burkholder et al. 1959). It is unclear whether this reflects enhanced leaf production in nutrient-rich fine sediments or the need for greater root development for increased nutrient absorption in the generally nutrient-poor coarse sediments. *Thalassia* has the most robust root and rhizome system of the Florida seagrasses. *Halodule* and *Syringodium* have shallower, less massive roots and rhizomes, and tend to have a greater portion of their total biomass, 50 to 60%, in leaves (Zieman 1982).

Productivity

Seagrasses are noted for their high primary productivity compared to other marine ecosystems. Values for seagrass productivity, like those of biomass, vary enormously depending on species, density, season, and measurement technique. Zieman (1982) and Zieman and Zieman (1989) provided detailed tables of productivity rates. Productivity values of <0.5 to 16 g C m^2/d have been reported for the South Florida region. The highest reported values (e.g., Odum 1963) reflect the production of seagrasses, epiphytic algae, and benthic algae. Measurement methods that are specific for seagrass production show that net, above-ground production is commonly 1 to 4 g C m^2/d, although maximum rates can be higher (Zieman and Wetzel 1980).

Recent explorations of the mechanisms underlying high seagrass productivity have uncovered patterns in species response and regional response. Seagrass productivity is governed largely by nutrient availability and the quantity and quality of light reaching the leaf surface. Williams and McRoy (1982) have shown that tropical and sub-tropical American and Caribbean species show two characteristic responses of productivity to light intensity, and these patterns complement the observed successional roles of the plants. *Syringodium* and *Thalassia* from Puerto Rico showed a relatively slow initial uptake and a relatively linear response throughout the range of irradiance tested, with no indication of inhibition at 100% irradiance. By contrast, *Halodule* had a higher initial rate which greatly increased at higher intensities, but with an indication of some inhibition at 100% irradiance (a pattern characteristic of an early colonizer). All species tested showed a pronounced regional effect, with tropical plants having much higher photosynthetic rates. Mean maximum carbon fixation rates in Puerto Rico were 2.96 mg C g dry wt/h for *Thalassia*, 3.33 for *Syringodium*, and 11.42 for *Halodule*; whereas in Texas, the relative rates were 1.38 for *Thalassia*, 1.35 for *Syringodium*, and 2.76 for *Halodule*.

Temporal and Spatial Patterns

The wide range of environmental conditions and seasonal programming throughout the range of seagrass species has a pronounced effect on their annual productivity and biomass cycles. **Figure 4.7** illustrates some seasonal patterns in a *Thalassia* bed throughout a 16-month period in south Biscayne Bay. Both productivity and standing crop vary seasonally, with high values in warm months and low values during winter. Highest standing crop values were about 2.5 to 3 times the winter minimum. This seasonality varies latitudinally, with a maximum to minimum leaf standing crop ratio of 1.2 to 2.5 on the northwestern coast of Cuba (Buesa 1974), 2 to 3 generally in South Florida (Zieman 1975a,b, 1982), and 6 to 8 for the northwest coast of Florida (Iverson and Bittaker 1986).

A major question in any ecosystem study is--what regulates productivity? With seagrasses of the Gulf and Caribbean, a pattern is beginning to emerge wherein areal productivity is a primary function of biomass and specific productivity, with specific productivity being a function of available light and nutrient supply. **Figure 4.8** shows the areal production of *Thalassia* as a function of biomass in Florida Bay (Zieman et al. 1989). This shows a significant linear relationship between production and standing crop, with an r^2 value of 0.91. The range of standing crop varied by a factor of 79:1, from 1.8 to 142.9 g dry wt/m^2, whereas the turnover rate, an analog of specific productivity (ratio of daily production to standing crop), varied by a factor of only 2.4:1, from 1.5 to 3.6% per day. Thus, there was little variation in turnover rate in South Florida over a wide range (two orders of magnitude) of biomass values. This shows that areal productivity is highly dependent on biomass within seagrass beds over a broad region.

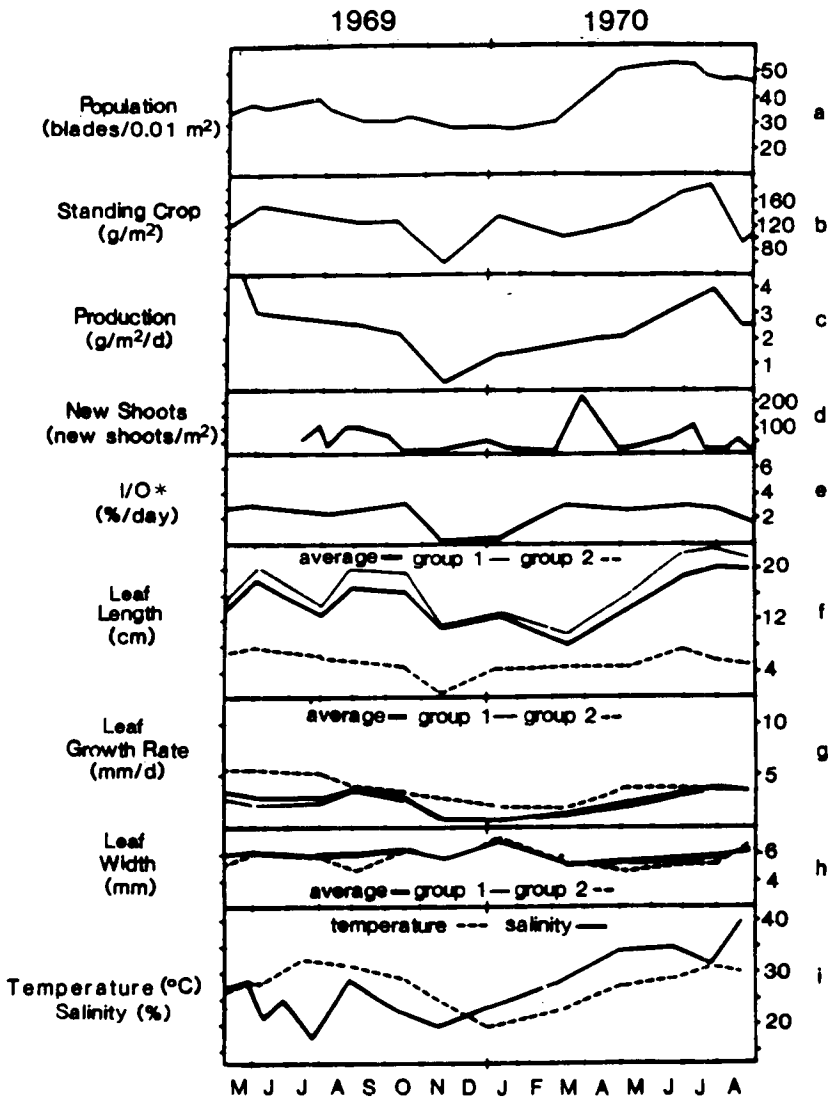
Chemical and Nutritive Constituents of Seagrasses

Because of their high productivity and wide distribution, seagrasses are a potentially important food source for other organisms in shallow coastal marine systems. The relative amount of protein in the plant tissues has been used as a measure of the potential food value of tropical seagrasses. Comparative studies have shown that turtle grass leaves are roughly equal in protein content to phytoplankton and Bermuda grass (Burkholder et al. 1959) and two to three times higher than 10 species of tropical forage grass (Vicente et al. 1980). Constituent analysis is also valuable in determining the physiological condition of the plant.

Various authors have performed such constituent analyses for the seagrasses considered herein (Burkholder et al. 1959; Bauersfeld et al. 1969; Walsh and Grow 1972; Lowe and Lawrence 1976; Bjorndal 1980; Dawes and Lawrence 1980; Vicente et al. 1980; Dawes and Lawrence 1983). A summary of these results is given by Zieman and Zieman (1989).

Patterns of variation of constituents, especially protein content, have been shown to vary both spatially and temporally (Dawes and Lawrence 1983; Dawes 1985; Dawes et al. 1985; Durako and Moffler 1985c). In Tampa Bay, values for *Thalassia* varied from 8 to 22% and values for *Syringodium* varied from 8 to 13%, with maximum values occurring in summer. *Thalassia* leaves collected in July 1979 from Tampa Bay, Key West, and Glovers Reef (Belize) showed a significant difference in protein content (higher in *Thalassia* leaves from Belize) even though the sites were similar in depth, salinity, and temperature (Dawes and Lawrence 1983).

In Tampa Bay, seasonal variation in soluble carbohydrate content occurred in rhizomes of both *Thalassia* and *Syringodium*, reflecting production and storage of starch during summer and fall (Dawes and Lawrence 1980). Mean values for the lipid content of *Thalassia* leaves varied from 1.2 to 4.2%, and were comparable to the fat content of tropical terrestrial grasses.



*I/O = turnover rate, or percent replacement of standing crop per day

Figure 4.7. Variation in temperature, salinity, and biotic seagrass parameters from a meadow in south Biscayne Bay (From: Zieman 1975a).

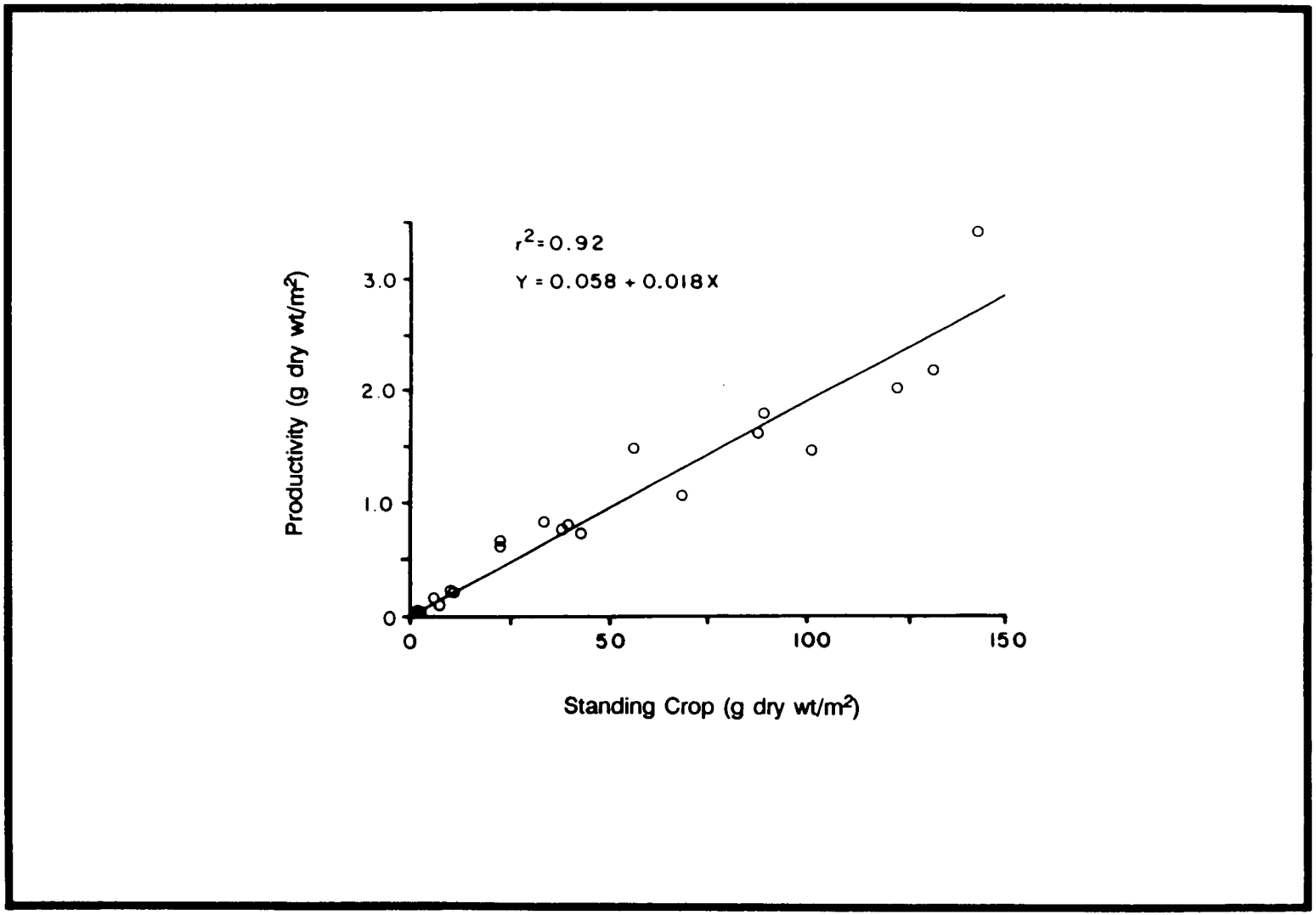


Figure 4.8. Relationship of areal productivity to standing crop of *Thalassia* in Florida Bay (From: Zieman et al. 1989). The slope of the line shows a daily mean rate of change of 2% over a wide range of standing crop.

Succession and Ecosystem Development

In the marine environment, very few plants have evolved the ability to colonize soft sediments. As a result, the successional sequence leading to seagrasses usually consists only of the seagrasses and rhizophytic green algae (den Hartog 1970, 1971; Zieman 1982). Seagrasses are vital to coastal environments because they are the only plants capable of providing the basis for a mature, productive ecosystem in these regions. Few other systems are so dominated and controlled by a single species as a climax *Thalassia* meadow. If the seagrass disappears, the entire associated community disappears with it; there is no other organism that can substitute, sustain, and support the ecosystem.

Initial colonizers of bare sediments (**Figure 4.9**) are typically rhizophytic macroalgae, of which various species of *Halimeda* and *Penicillus* are the most common, although species of *Caulerpa*, *Udotea*, *Rhipocephalus*, and *Avrainvillea* also occur. These algae have some sediment-binding capability, but because they do not form a dense canopy or rhizoidal mat, their ability to stabilize sediments is minimal. Their major function in the early successional stage seems to be contribution of sedimentary particles as they die and decompose.

Halodule wrightii, the local pioneer species of seagrasses, colonizes readily either from seed or rapid vegetative branching. The numerous leaves and denser root and rhizome mat form a better buffer to protect the integrity of the sediment surface than the algal communities. In some sequences, *Syringodium* will appear next, intermixed with *Halodule* at one edge of its distribution and *Thalassia* at the other. However, *Syringodium* is the least constant member of this sequence and is frequently absent. In areas with consistent disturbance and sediments low in organic content, *Syringodium* may become the dominant species. It commonly lines natural channels with higher velocity waters and higher turbidity than *Thalassia* can tolerate.

As successional development proceeds, *Thalassia* begins to colonize the region. Its broad, strap-like leaves and massive rhizome and root system efficiently trap and retain particles, increasing organic matter in sediments. Sediment height rises until the rate of deposition and erosion of sediment particles is in balance. This rate is a function of the intensity of wave action, current velocity, and leaf density.

In shallow-water successional sequences leading to *Thalassia*, the early stages are often characterized by low sediment organic matter and open nutrient supply; that is, the community relies on nutrients brought in from adjacent areas by water movement as opposed to *in situ* regeneration. With the progression from rhizophytic algae to *Thalassia*, there is a progressive increase in the below-ground biomass of the community. In addition, the progressive increase in leaf area of the plants promotes sediment trapping and particle retention. This material adds organic matter to further fuel the sedimentary microbial cycles and adds to the nutrient pools.

In summary, succession of dominant plant species in these systems results in important structural and functional changes. Increased leaf area provides more substrate for epiphytic algal and faunal colonization, while promoting sedimentation and increasing total organic content of the system. As the canopy component increases, so do the below-ground biomass and the nutrients stored in the sediments. *Thalassia*, the climax species, has the highest leaf area, the highest total biomass, and by far the greatest amount of material in sediments of any successional stage, and consequently can support the highest biomass and diversity of associated organisms.

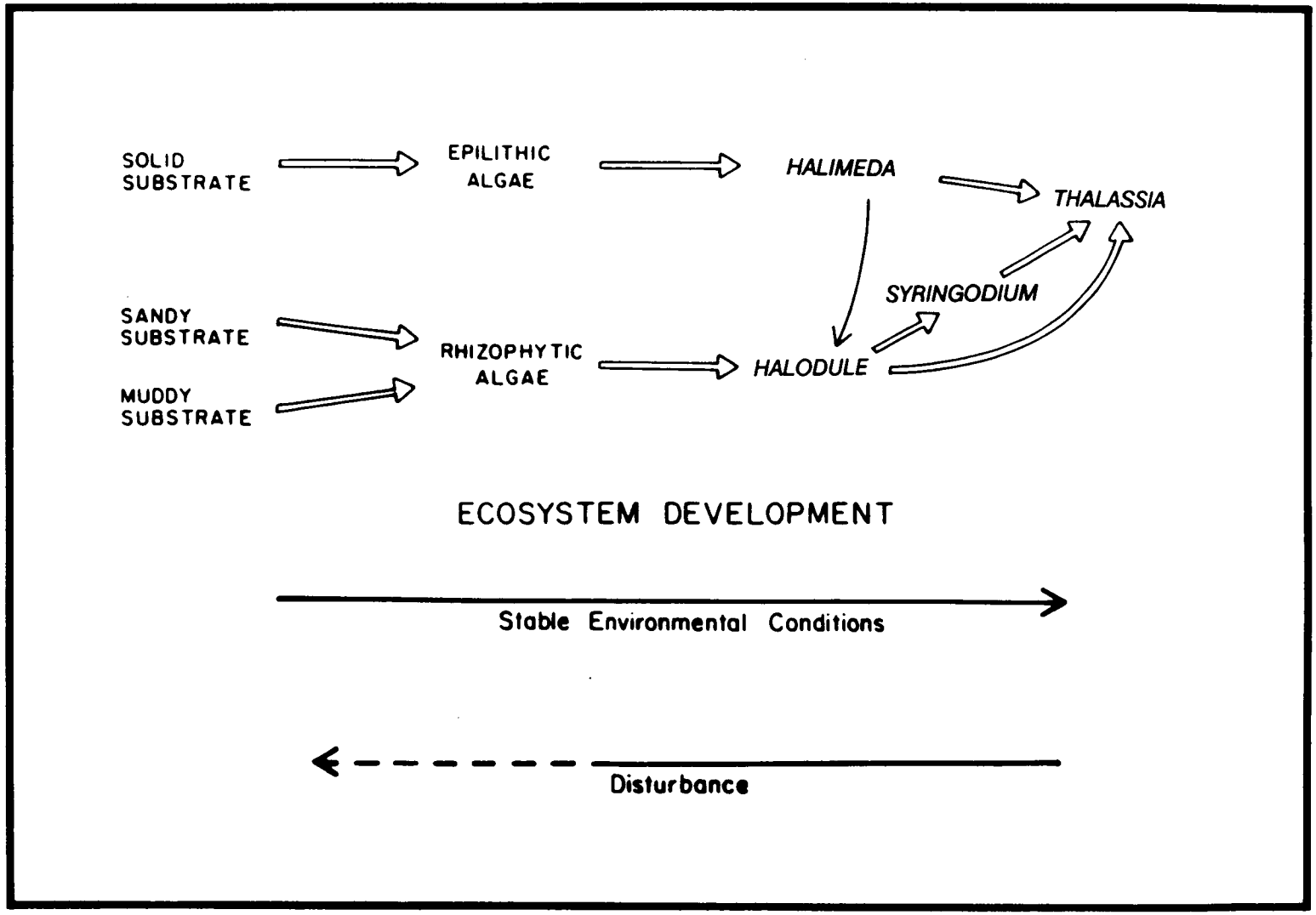


Figure 4.9. Potential pattern of successional development in a Caribbean seagrass bed (From: den Hartog 1970; Zieman 1982). All stages are not present in all seagrass developmental sequences.

Seagrass Community Ecology

Community Components and Relationships

The distribution and density of seagrass species are dependent on the physical, chemical, and geological environment. The associated community is the product of this seagrass composition as well as the abiotic variables. The principal groups are (1) epiphytic organisms, (2) epibenthic organisms, (3) infaunal organisms, (4) planktonic organisms, and (5) nektonic organisms.

Most intimately associated with the seagrasses themselves are the epiphytes. The relationship between epiphyte and seagrass host is basically that of an ectoparasite, being beneficial to the epiphytic ectoparasite, but detrimental to the seagrass host (Humm 1964; Harlin 1975, 1980). While epiphytes derive benefits such as being raised higher in the photic zone, the shading effect of the epiphytes has been shown to be detrimental to the seagrass hosts (Sand-Jensen 1977; Orth and van Montfrans 1984). In areas of high epiphyte growth, the action of epiphyte grazers is extremely important in maintaining seagrass productivity as well as longevity of the host seagrasses, without which the system would be eliminated (Orth and van Montfrans 1984). Epiphytic diatom associations in Florida Bay have been described by DeFelice and Lynts (1978).

The standing crop and productivity of seagrass epiphytes and their resultant contribution to the trophic base of the system are highly variable. In some areas, such as immediately behind a coral reef, there are few epiphytes and little contribution. In other areas, especially those with high external nutrient enrichment, the amount of production is quite high and lethal to the seagrasses (Harlin and Thorne-Miller 1981).

The invertebrate fauna of seagrass beds of the Southwest Florida coast is primarily Caribbean-West Indian, with increasing input from Carolinian fauna from the north (Collard and D'Asaro 1973). There is a greater proportion of emergent organisms (those living at or above the sediment surface) than infaunal organisms (those living in the sediment) in the seagrass beds of the southern part of the West Florida coast, changing to a lesser proportion of dominant emergent forms in the north.

Early ecological surveys of Florida coastal waters include observations of increased densities of fish and invertebrates within seagrass beds compared to adjacent habitats (Reid 1954; Tabb et al. 1962; Roessler 1965). Later studies quantified these differences in faunal abundance (Roessler et al. 1974; Yokel 1975a,b; Thorhaug and Roessler 1977; Weinstein and Heck 1979). The concise study of Yokel (1975a,b) serves to characterize these results. In Rookery Bay Sanctuary, more than three times as many fish were captured in seagrass than in bare sand and shell substrates (**Figure 4.10**). Standing crop of crustaceans (estimated from trawls) was nearly four times larger in mixed seagrass and algal flats than on nearby unvegetated bottoms (Yokel 1975a,b). Stoner (1980) found that the density of macrofaunal organisms and the number of species taken was directly related to the density of macrophyte biomass. Faunal dominance was different between the vegetated and unvegetated stations. When comparing strictly infaunal organisms, a different pattern may appear. Stoner (1983) found that the relative abundances of infaunal organisms decreased in the following order:

Sand > *Halodule* > *Syringodium* > *Thalassia*

as well as from low to higher biomass of the seagrasses. Virnstein et al. (1983), Virnstein (1987), and Zieman and Zieman (1989) provide recent reviews.

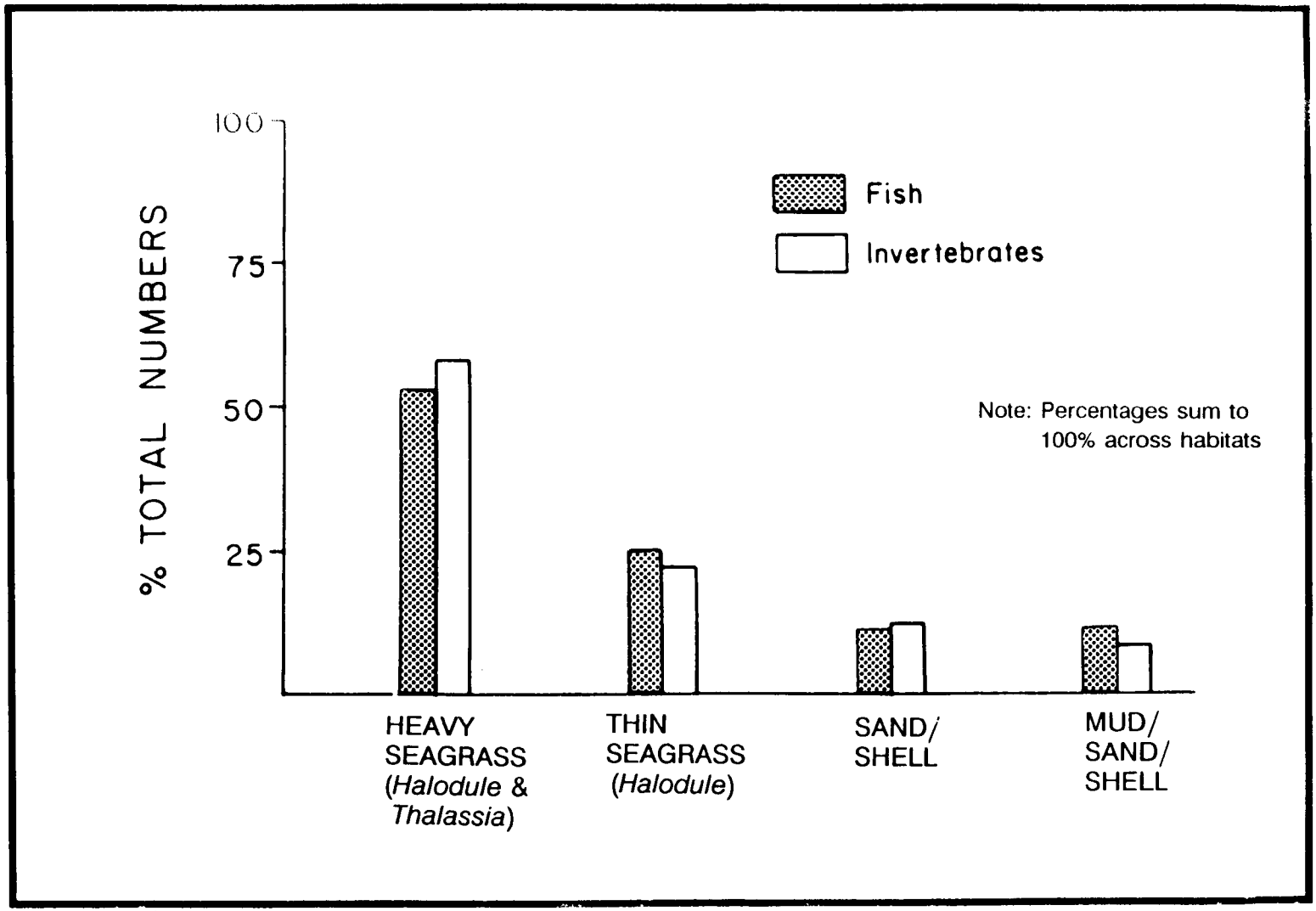


Figure 4.10. Relative abundances of invertebrates and fish in seagrass beds and adjacent non-vegetated habitats in Rookery Bay (From: Yokel 1975a).

Seagrasses and associated epiphytes provide food for trophically higher organisms by means of three distinct routes: (1) direct herbivory, (2) detrital food webs within seagrass beds, and (3) export of material from the system for utilization by organisms outside of seagrass beds. Even though seagrasses have a relatively high protein content, they are directly grazed by relatively few animals. Occasionally, localized grazing by sea urchins, parrotfishes, green turtles, or manatees can be quite significant (Camp et al. 1973; Greenway 1976; Ogden 1980; Thayer et al. 1984; Zieman and Zieman 1989).

One of the most important roles that seagrass beds have in the coastal ecosystem is that of a nursery ground in which postlarval fish and invertebrates concentrate and develop. In addition, important species such as the spotted seatrout (*Cynoscion nebulosus*) spawn in or just adjacent to seagrass beds (Tabb 1966; Lassuy 1983; Lewis et al. 1985b). Seagrass habitats offer high productivity, surface areas, and blade densities, as well as a rich and varied flora and fauna. Based on abundance and size data, many important species prefer seagrass habitat over available alternatives in estuaries and coastal lagoons (Yokel 1975a). In Tampa Bay, 23 species of finfish, crabs, and shrimp of major importance in Gulf of Mexico fisheries were found as immature forms in seagrass beds (Sykes and Finucane 1966). A third of the species collected at Matecumbe Key seagrass beds by Springer and McErlean (1962b), including all filefishes, grunts, parrotfishes, and snappers, occurred only as young, indicating the nursery value of the seagrass-dominated shoreline habitat sampled. Studies throughout Southwest Florida estuaries of Rookery Bay, Marco Island, and Fakahatchee Bay have shown that shrimp were most abundant at stations dominated by seagrasses. Within these stations, shrimp were most abundant where benthic vegetation was dense (Yokel 1975a,b).

Export

Seagrass leaves are frequently detached and transported away from the beds. Large quantities are found among mangroves, in wrack lines along beaches, floating in large mats, and collected in depressions on unvegetated bottom. In exposed areas, leaves and even large chunks of leaf, rhizome, and sediment can be detached by storm action. In clear tropical waters, a major source of leaf detachment is by the action of grazers on the leaves. In Tague Bay, grazing by parrotfishes and sea urchins created large drift lines of exported seagrass blades. Because of *Thalassia's* higher density, only about 1% of its daily production was exported, whereas 60 to 100% of the highly buoyant *Syringodium* was exported from a tropical bay (St. Croix, U.S. Virgin Islands) (Zieman et al. 1979).

The export described above is typical in that *Syringodium* constitutes the major portion of drift material, although it may be a small proportion of the donor beds. *Syringodium* contains large air spaces and can remain afloat for long periods, whereas *Thalassia* rarely floats for more than a day. In the Indian River, Fry (1984) found that 47% of the *Syringodium* was transported from beds there. As this was the major seagrass, he concluded that this in part led to a higher reliance trophically on algal components of the food web than seagrass material.

Off the west coast of South Florida, vast rafts of drifting seagrasses can be seen at times emanating for several hundred kilometers from Florida Bay (**Figure 4.11**). Exported seagrass contributes nutritive material to the highly productive shrimping grounds of the region (Zieman 1982; Zieman et al. 1989).

Environmental Stresses

The primary environmental variables limiting the distribution and abundance of seagrasses in South Florida have been described in a previous section. For seagrass growth and existence, there is an optimal value of each environmental parameter. Using seagrass productivity as an indicator of health and response, comparison of temperature and salinity effects serves to indicate the range in response to environmental parameters.

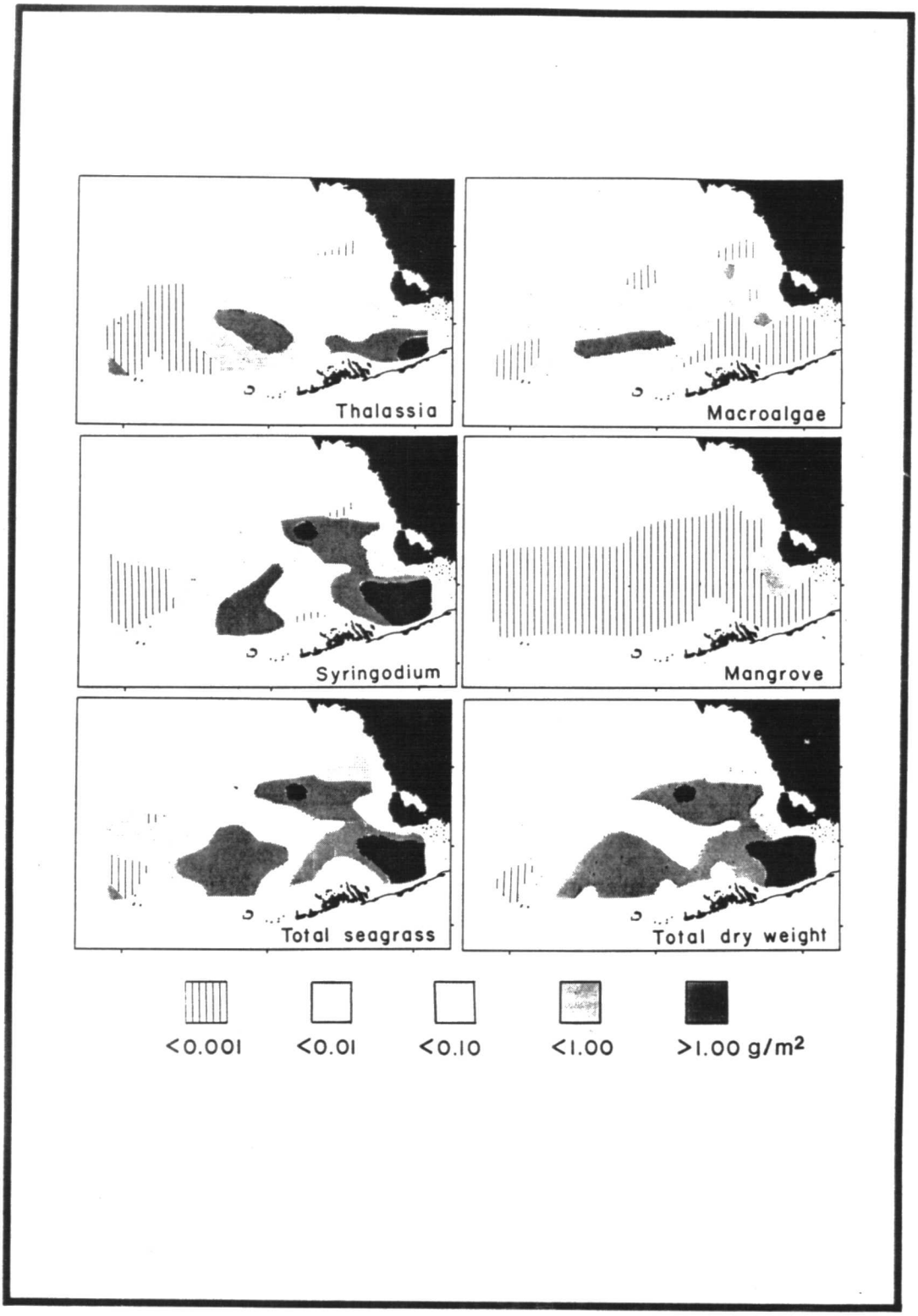


Figure 4.11. Density of macrophyte drift material in surface waters west of Florida Bay in October 1979 (From: Zieman et al. 1989).

Figure 4.5 shows the responses of *Thalassia* to temperature and salinity (Zieman 1975a). The response of productivity to temperature is pronounced, with small departures from the optimum radically decreasing net productivity. By comparison, even relatively large departures from the optimum salinity have relatively small effects.

Most environmental stresses that affect seagrasses, whether caused by human intervention or by extreme excursions of natural processes, are simply perturbations of the ranges of natural environmental variables such as light and temperature, or in the concentrations of nutrients. Acute stresses such as removal of a bed by dredging or burial of a bed with fill material will kill a seagrass bed rapidly. Similarly, if the local salinity drops from 30 ppt to near 0 ppt due to a release of fresh water from an impoundment (as recently happened in Manatee Bay and Barnes Sound), seagrass leaves and virtually all algae will be rapidly killed. Extreme temperature increases or exposure will have similar results. Generally, these extreme events will devastate *seagrass communities*, but will cause only defoliation or leaf death in *seagrasses*. This is because seagrass meristems are protected in sediments. If the stress is relieved, seagrasses will recover and replace the leaf canopy. If the stress is continued, the below-ground tissues will also eventually die.

Lower-level chronic stresses, such as elevated temperatures or subtly increased turbidity, cause reduced productivity or eventually death over long periods of time. Generally, these stresses act by either decreasing gross productivity, increasing respiration, or both. If the stress is great enough or is sufficiently prolonged, the plant dies, essentially of starvation.

Historically, the greatest losses of seagrasses in South Florida have been due to dredging and filling, primarily to build residential and industrial developments. Canals were dredged deep, to create more fill for development, and usually yielded bottoms that were too deep, and thus, too deeply shaded to allow recolonization. In more recent years, this type of development has been greatly reduced, but seagrass loss continues. Today, the primary loss of seagrass habitat results from increased turbidity and subsequent shading. In some areas of South Florida, this is due to suspended fine sediments; elsewhere, it is due to eutrophication from inadequate sewage treatment or due to septic tank leakage from porous bedrock of housing canals. In some cases, the excess nutrients cause phytoplankton growth in the water, while in other cases, they stimulate excess epiphyte development on the leaves. The ultimate effect is the same, i.e., continued stress and eventual death of the plant.

Another major source of seagrass bed loss and disturbance is physical damage by boats. Scarring of seagrass beds has long been recognized as a major disturbance (Zieman 1976). Even small cuts from boat propellers can take five or more years to heal in a mature and healthy *Thalassia* bed. More extensive damage from large-scale prop dredging can take decades to recover.

Most of the anthropogenic stresses to which seagrasses are subjected are abnormal or extreme extensions of environmental stresses to which the plants are adapted, thermal pollution being a prime example. Some of these are treated in the previous section and others are merely extensions of the sections on Limiting Variables and Distributional Controls. Other anthropogenic stresses, of which a primary one is due to oil spills and cleanup efforts, are stresses that are outside of the range of seagrass evolution. Crude oil seems to kill, much like burial, but the effects of the more volatile and soluble oil fractions are not yet well understood (Zieman et al. 1984b). It is certain, however, that shallow and just-subtidal seagrass beds, which abound in the study area, are the most susceptible to such damage.

Compared with other coastal interface communities, seagrass meadows are not generally the most susceptible to damage from oil spills except at their upper ranges of distribution. Where oil has contacted seagrasses that are just intertidal or just subtidal,

damage has been extensive, while deeper subtidal beds are generally unharmed by direct effects of the oil (Chan 1977; Cubit et al. 1987; Jackson et al. 1989). These instances point out how vulnerable much of South Florida's seagrass meadows would be to an oil spill. Many of the deeper seagrass beds, such as those of the deeper back reef areas or in Hawk Channel, would probably survive, but the priceless nursery meadows of Florida Bay in Everglades National Park and much of the western portions of the Lower Keys could be destroyed. This is because so much of this area consists of shallow mudbanks that are emergent on very low tides. **Figure 4.12a**, taken from Zieman et al. (1989), shows a map of Florida Bay depicting the relative distribution of seagrass- covered mudbanks (stippled) and the deeper (1 to 3 m) basins. **Figure 4.12b** shows vertical relief along the same transect in cross-section. *Thalassia* occurred at 95% of all stations sampled in Florida Bay. The average standing crop of leaves for the entire bay was 63.2 g dry wt/m^2, whereas the density in the upper meter of the western section of the bay, which would be by far the most vulnerable to oil spills, is 125 g dry wt/m^2 (Zieman et al. 1989).

The effects of various types of damage to seagrasses have been extensively reviewed elsewhere, with examples and case studies described. General reviews of stress and pollutant effects on seagrasses are provided by Zieman (1975b), Zieman (1982), and Zieman and Zieman (1989). For effects of thermal pollution, see Zieman and Wood (1975); and for effects of oil on seagrasses, see Zieman et al. (1984b), as well as sections herein which document the effects of recent oil spills on tropical seagrass communities. Livingston (1987) has documented the historic losses of seagrasses in Florida related to human development and exploitation. For further discussion of oil spill effects on seagrasses, see **Chapter 15**.

Conclusions

The South Florida region is unique for the U.S. and environmentally valuable in numerous ways. Most often cited is the unique and distinctive tropical beauty associated with its clear waters and distinctive fauna and flora. Thus, it is deserving of protection solely because of its aesthetics and beauty. Vital commercial and recreational fisheries depend on the shallow seagrass beds of the region for support. An oil spill that destroyed seagrass beds in this region could have devastating effects on the vitally important pink shrimp and lobster fisheries, as well as seatrout and redfish. The recent experience in Alaska (*Exxon Valdez* spill) has conclusively demonstrated that the only currently feasible way to protect resources such as these is to never allow them to be disturbed. After-the-fact cleanup of ecosystems of this importance, delicacy, and physical extent (the seagrass beds of Florida Bay alone are 1,860 km^2) is not feasible.

Twenty years ago, few people knew or cared about the fate of seagrasses. Today, scientists, management agencies, and conservationists all recognize the role of these plants in the coastal ecosystem. Research has been progressing to the point that it is usually possible to determine the *qualitative* effects of natural environmental and anthropogenic stresses. It is still vitally necessary to develop information to allow *quantitative* assessments as well. The list below identifies some of the most critical needs for rational understanding and management of seagrass ecosystems. Many of the ideas are not just those of the author, but are recommendations of the Florida Seagrass Task Force, commissioned by the Secretary of the Department of Environmental Regulation, of which the author was a member.

Light

Potentially the most important need is to understand how modifications of the light field affect seagrass growth and health. Intuitively, this is a simple relationship: any anthropogenically caused decrease in the quality or quantity of submerged light is *always* detrimental to seagrasses. However, the particular effects on any specific seagrass bed

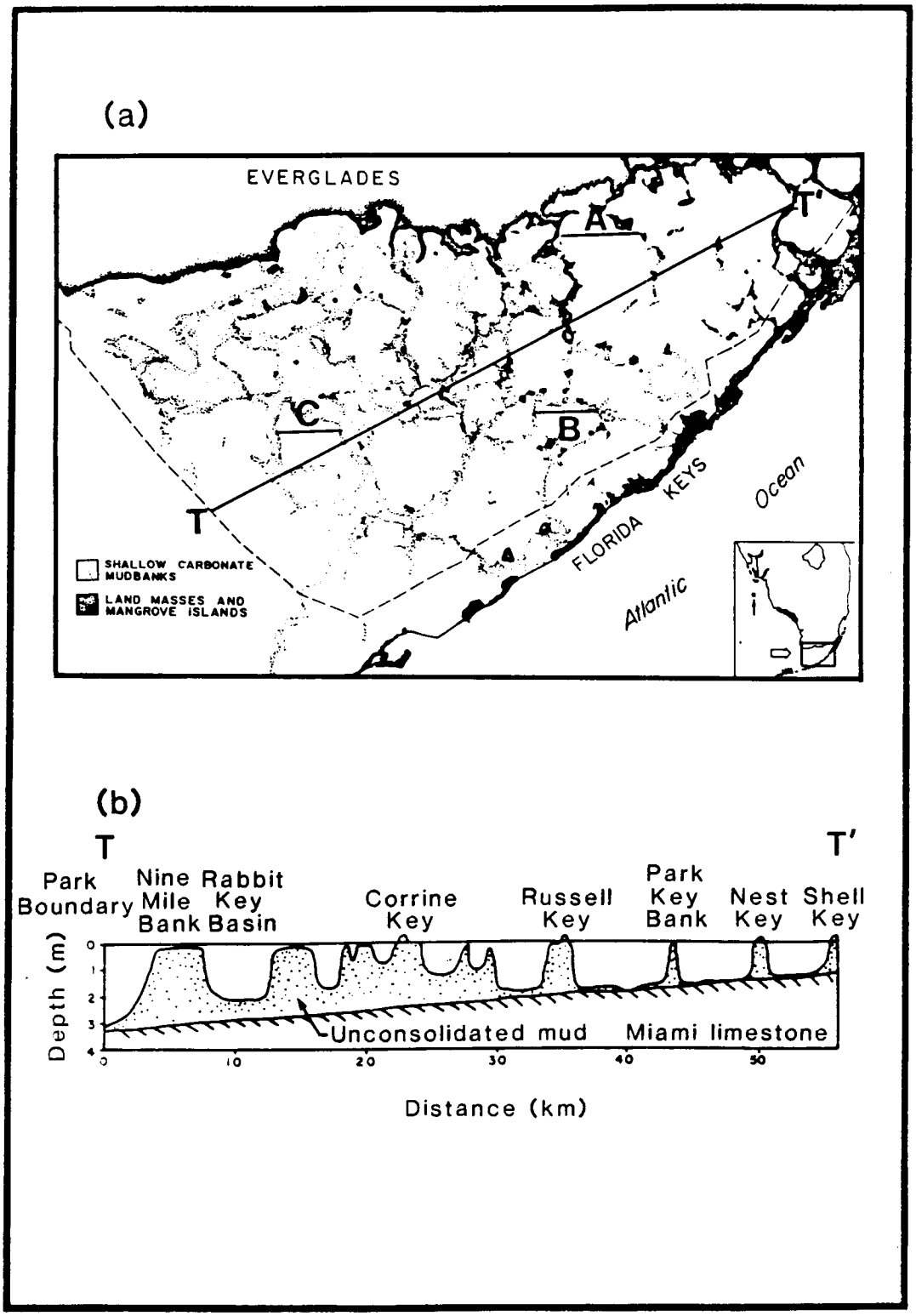


Figure 4.12. (a) Distribution of shallow mudbanks (stippled) and deeper basins (clear) in Florida Bay (From: Zieman et al. 1989). Seagrass beds on the shallow mudbanks would be the most susceptible to damage and destruction from oil contamination. (b) Cross section of of transect T from Figure 4.13(a). Note the increasing concentration of shallow mudbanks in the western portion of the Bay.

cannot be determined at this time. More information is needed concerning (1) the effects of quantitatively reducing the light field, and (2) the effects of qualitatively changing the spectrum of light reaching the plants. It is relatively simple to place seagrasses in a test aquarium and reduce light by using neutral gray screens to determine changes in photosynthetic rate. However, it is vitally necessary to understand the effects of (1) suspended sediments, (2) eutrophic phytoplankton growth, and (3) eutrophic epiphytic growth on these same plants.

At this point, it can be strongly stated from observation by trained observers that increases in turbidity caused by suspended sediments and eutrophic algal growth are detrimental to seagrasses; but the relative importance of each, and how they interact, is not known. It is the opinion of the author that chronic deterioration of water quality due to eutrophication and suspended sediments is the greatest source of seagrass losses at present.

Long-Term Studies

Seagrasses have not been monitored for extended periods of time. Thus, no information exists on long-term *natural* variation in undisturbed seagrass meadows. It is currently impossible to separate the effects of random but extreme climatic events from those caused by anthropogenic stresses and habitat modification.

The need for this type of information has been emphasized during the past 18 months. Since the summer of 1987, a massive die-off of seagrasses, primarily *Thalassia*, has occurred in Florida Bay and other parts of South Florida. In Florida Bay, over 4,047 ha have been totally destroyed and denuded, and an additional 24,282 ha have been severely damaged. This event is being investigated by a team assembled by the Everglades National Park (Zieman et al. 1988), but it is largely an after-the-fact study. Little applicable information exists on the previous condition of the areas in which the die-off occurred.

A conspicuous gap exists in the knowledge of long-term effects of water management practices in South Florida on seagrass communities, particularly in Florida Bay. Beginning with the Flagler railway and continuing through present-day control of water levels and hydroperiod, there is evidence that salinities in Florida Bay have been altered since historical times. Specific effects on seagrass communities and on associated fauna need to be understood to determine the optimum, water management regime.

Succession and Community Development

Numerous data gaps exist concerning succession and community development. The broad pattern of succession has been described, but the conditions which lead to the transition of one species to another are not quantified. In addition, the relative roles of (1) vegetative reproduction (clonal growth), (2) seed and seedling success, and (3) rooting of free vegetative segments in maintaining and dispersing seagrass beds is unknown. If spreading and reproduction are largely clonal, the reduced genetic diversity could have important effects on the ability of a bed to tolerate various stresses.

Models

For knowledge and predictability of seagrass systems to advance, it is necessary to develop conceptual and simulation models of the most important processes. Primary among these processes are the interaction of light, temperature, and salinity on seagrass growth, as well as models describing successional processes. These will allow scientists and managers to generalize rather than rely totally on innumerable site-specific studies.

REFERENCES CITED

Adey, W. 1977. Shallow water Holocene bioherms of the Caribbean Sea and West Indies. In *Proceedings, Third International Coral Reef Symposium, Miami* 2:xxi-xxiv. Miami: Rosenstiel School of Marine and Atmospheric Sciences, Univ. of Miami.

Agassiz, A. 1883. The Tortugas and Florida reefs. *Mem. Am. Acad. Arts Sci.* 11:107-134.

Alongi, D. M. 1987. The influence of mangrove-derived tannins on intertidal meiobenthos in tropical estuaries. *Oecologia* (Berlin) 71:537-540.

Antonius, A. 1974. New observations on coral destruction in reefs. Paper read at 10th Meeting of the Association of Island Marine Laboratories of the Caribbean, 4-7 Sept. 1973, at Mayaguez, Puerto Rico.

Antonius, A. 1976. Kranke Korallen: Riffzerstorung. *Umsch. wiss. Tech.* 76:493-494.

Antonius, A. 1981a. Coral pathology: A review. In *Proceedings, Fourth International Coral Reef Symposium, Manila*, 2:3-6. Quezon City, The Philippines: Paragon Printing Corp.

Antonius, A. 1981b. The "band" diseases in coral reefs. In *Proceedings, Fourth International Coral Reef Symposium, Manila*, 2:7-14. Quezon City, Philippines: Paragon Printing Corp.

Antonovics, J., A. D. Bradshaw, and R. G. Turner. 1971. Heavy metal tolerance in plants. *Adv. Ecol. Res.* 7:1-85.

Atkinson, M. J., and R. W. Grigg. 1984. Model of a coral reef ecosystem II. Gross and net benthic primary production at French Frigate Shoals, Hawaii. *Coral Reefs* 3:13-22.

Bak, R. P. M., and G. Van Eys. 1975. Predation of the sea urchin *Diadema antillarum* Phillippi on living coral. *Oecologia* 20:111-115.

Bak, R. P. M., M. J. E. Carpay, and E. D. de Ruyter van Steveninck. 1984. Densities of the sea urchin *Diadema antillarum* before and after mass mortalities on the coral reefs of Curacao. *Mar. Ecol. Prog. Ser.* 17:105-108.

Bak, R. P. M., J. Sybesma, and F. C. VanDuyl. 1981. The ecology of the compound ascidian *Trididemnum solidum*. 2. Abundance, growth and survival. *Mar. Ecol. Prog. Ser.* 6(1):43-52.

Bak, R. P. M., R. M. Termaat, and R. Dekker. 1982. Complexity of coral interaction: Influence of time, location of interaction, and epifauna. *Mar. Biol.* 69:215-222.

Ball, M. M., E. A. Shinn, and K. W. Stockman. 1967. The geologic effects of Hurricane Donna in South Florida. *J. Geol.* 75:583-597.

Banus, M. D., and S. E. Kolehmainen. 1976. Rooting and growth of red mangrove seedlings from thermally stressed trees. In *Thermal Ecology II: Proceedings of Symposium, Augusta, Georgia, 1975*, ed. G. W. Esch and R. W. McFarlane, 46-53. Technical Information Center, Energy Research and Development Administration.

Barber, B. J., and P. J. Behrens. 1985. Effects of elevated temperature on seasonal *in situ* leaf productivity of *Thalassia testudinum* Banks ex Konig and *Syringodium filiforme* Kutzing. *Aquat. Bot.* 22:61-69.

Barnes, D. J. 1973. Growth in colonial scleractinians. *Bull. Mar. Sci.* 23:280-298.

Barnes, D. J., and C. J. Crossland. 1980. Diurnal and seasonal variations in the growth of a staghorn coral measured by time lapse photography. *Limnol. Oceanogr.* 25:1113-1117.

Barth, H. 1982. The biogeography of mangroves. In *Contributions to the ecology of halophytes*, ed. D. N. Sen and K. S. Rajpurohit, 35-60. The Hague: Dr. W. Junk Publishers.

Bauer, J. C., and C. J. Agerter. 1987. Isolation of bacteria pathogenic for the sea urchin *Diadema antillarum* (Echinodermata: Echinoidea). *Bull. Mar. Sci.* 40(1):161-165.

Bauersfeld, P., R. R. Kleer, N. W. Durrant, and J. E. Sykes. 1969. Nutrient content of turtle grass (*Thalassia testudinum*). *Proc. Int. Seaweed Symp.* 6:637-645.

Bayer, F. 1961. *The Shallow-Water Octocorallia of the West Indian Region*. The Hague, Netherlands: Martin Nijhoff.

Berner, R. A., and J. W. Morse. 1974. Dissolution kinetics of calcium carbonate in seawater. IV: Theory of calcite dissolution. *Am. J. Sci.* 274:108-134.

Bernstein, L. 1961. Osmotic adjustment of plants to saline media. 1. Steady state. *Am. J. Bot.* 48:909-918.

Birkeland, C. 1977. The importance of rate of biomass accumulation in early successional stages of benthic communities to the survival of coral recruits. In *Proceedings, Third International Coral Reef Symposium, Miami*, 1:16-21. Miami: Rosenstiel School of Marine and Atmospheric Sciences, Univ. of Miami.

Birkeland, C. 1987. Nutrient availability as a major determinant of differences among coastal hard-substratum communities in different regions of the tropics. In *Differences between Atlantic and Pacific tropical marine coastal ecosystems: Community structure, ecological processes, and productivity*, 45-90. Unesco Rep. Mar. Sci.

Bjorndal, K. 1980. Nutrition and grazing behavior of the green turtle, *Chelonia mydas*. *Mar. Biol.* 56:147-154.

Blair, S. M., and B. S. Flynn. 1988. *Sunny Isles beach restoration project: mechanical damage to the reefs adjacent to the borrow area*. Metro Dade Tech. Rep. 88-14.

Blank, R. J., and R. K. Trench. 1985. Speciation and symbiotic dinoflagellates. *Science* 229:656-658.

Blasco, F. 1977. Outlines of ecology, botany and forestry of the mangals of the Indian subcontinent. In *Ecosystems of the world, Vol. 1. Wet coastal ecosystems*, ed. V. J. Chapman, 241-260. New York: Elsevier Sci. Publ. Co.

Blasco, F. 1983. *Mangroves of The Gambia and Senegal: Ecological status-evolution*. Report prepared for United Nations Sahelian Office. 1, United Nations Plaza, New York 10077. C.N.R.S./Universite Paul Sabatier, Toulouse, France.

Bradbury, R., and R. Richelt. 1981. The reef and man: rationalizing management through ecological theory. In *Proceedings of the Fourth International Coral Reef Symposium*, 1:219-223. Quezon City: Paragon Printing Corp.

Brawley, S. H., and W. H. Adey. 1981. The effect of micrograzers on algal community structure in a coral reef microcosm. *Mar. Biol.* 61:67-177.

Breen, C. M., and B. J. Hill. 1969. A mass mortality of mangroves in the Kosi estuary. *Trans. R. Soc. S. Afr.* 38:285-303.

Bright, T., W. Jaap., and C. Cashman. 1981. Ecology and management of coral reefs and organic banks. In *Proceedings of environmental research needs in the Gulf of Mexico*, 53-160. Miami: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, E.R.L.

Bromley, R. G. 1978. Bioerosion of Bermuda reefs. *Palaeogeogr., Palaeoclimatol., Palaeoecol.* 23:169-197.

Bryan, P. G. 1973. Growth rate, toxicity and distribution of the encrusting sponge, *Terpios* sp. (Hadromerida: Subertides) in Guam, Mariana Islands. *Micronesica* 9:237-242.

Buesa, R. J. 1974. Population and biological data on turtle grass (*Thalassia testudinum* Konig, 1805) on the northwestern Cuban shelf. *Aquaculture* 4:207-226.
Buesa, R. J. 1975. Populations, biomass and metabolic rates of marine angiosperms on the northwestern Cuban shelf. *Aquat. Bot.* 1:11-23.
Bunt, J. S. 1982. Studies of mangrove litter fall in tropical Australia. In *Mangrove ecosystems in Australia: Structure, function and management. Proceedings of the Australian National Mangrove Workshop*, ed. B. F. Clough, 223-237. Canberra: Australian National Univ. Press.
Burkholder, P. R., L. M. Burkholder, and J. A. Rivero. 1959. Some chemical constituents of turtle grass, *Thalassia testudinum*. *Bull. Torrey Bot. Club* 86(2)88-93.
Buss, L. 1980. Bryozoan overgrowth interactions: the interdependence of competition for space and food. *Nature* 281:475-477.
Cairns, S., and G. Stanley. 1983. Ahermatypic coral banks: living and fossil counterparts. In *Proceedings of the Fourth International Coral Reef Symposium*, 1:611-618. Quezon City: Paragon Printing Corp.
Cameron, A. 1974. Toxicity phenomena in coral reef waters. In *Proceedings, Second International Coral Reef Symposium, Brisbane*, ed. A. Cameron, B. Campbell, A. Cribb, R. Endean, J. Jell, O. Jones, P. Mather, and F. Talbot, 1:513-518. Brisbane, Queensland, Australia: The Great Barrier Reef Committee.
Cameron, A. M., B. M. Campbell, A. B. Cribb, R. Endean, J. S. Jell, O. A. Jones, P. Mather, and F. H. Talbot, ed. 1974. Proceedings of the Second International Coral Reef Symposium. Brisbane, Queensland, Australia: The Great Barrier Reef Committee.
Camilleri, J. C., and G. Ribi. 1986. Leaching of dissolved organic carbon (DOC) from dead leaves, formation of flakes from DOC, and feeding on flakes by crustaceans in mangroves. *Mar. Biol.* 91: 337-344.
Camp, D. K., S. P. Cobb, and J. F. Van Breedveld. 1973. Overgrazing of seagrasses by a regular urchin, *Lytechinus variegatus*. *BioScience* 23(1):37-38.
Capone, D. K., and B. F. Taylor. 1980. Microbial nitrogen cycling in a seagrass community. In *Estuarine perspectives*, ed. V. S. Kennedy, 153-162. New York: Academic Press.
Capone, D. G., P. A. Penhale, R. S. Oremland, and B. F. Taylor. 1979. Relationship between productivity and N_2 (C_2H_2) fixation in a *Thalassia testudinum* community. *Limnol. Oceanogr.* 24:117-125.
Carter, M. R., L. A. Burns, T. R. Cavinder, K. R. Dugger, P. L. Fore, D. B. Hicks, H. L. Revells, and T. W. Schmidt. 1973. *Ecosystems analysis of Big Cypress Swamp and estuaries*. EPA 904/9-74-002. Atlanta: U.S. Environmental Protection Agency, Region IV.
Chalker, B. E. 1983. Calcification by corals and other animals on the reef. In *Perspectives on Coral Reefs*, ed. D.J. Barnes, 29-45. Townsville, Queensland, Australia: Brian Clouston.
Chalker, B. E., T. Cox, and W. C. Dunlap. 1984. Seasonal changes in primary production and photoadaptation by the reef building coral *Acropora granulosa* on the Great Barrier Reef. In *Marine Plankton and Productivity*, ed. O. Holm-Hansen, L. Bolis, and R. Giles, 73-87. Berlin: Springer-Verlag.
Chan, E. I. 1977. Oil pollution and tropical littoral communities: Biological effects of the 1975 Florida Keys Oil spill. In *Proceedings, 1977 Oil Spill Conference*, 539-542. Washington, DC: American Petroleum Institute.
Chaplin, C., and P. Scott. 1972. *Fish watchers' guide to Western Atlantic coral reefs*. Wynnewood: Livingston Publ. Co.
Chapman, V. J. 1976. *Mangrove vegetation*. Germany: Strauss and Cramer.
Choat, J. H., D. J. Barnes, M. A. Borowitza, J. C. Coll, P. J. Davies, P. Flood, B. G. Hatcher, D. Hopley, P. A. Hutchings, D. Kinsey, G. R. Orme, M. Pichon, P. F. Sale, P. W. Sammarco, C. C. Wallace, C. R. Wilkinson, E. Wolanski, and O. Bellwood, ed. 1988. *Proceedings of the Sixth International Coral Reef Symposium, Townsville*. Queensland, Australia.
Choi, and R. N. Ginsburg. 1983. Distribution of coelobites (cavity dwellers) in coral rubble across the Florida Reef Tract. *Coral Reefs* 2:165-172.
Chornesky, E., and S. Williams. 1983. Distribution of sweeper tentacles on *Montastraea cavernosa*. In *The ecology of deep and shallow coral reefs*, ed. M. Reaka, 61-67. Rockville: NOAA Symposium for Underwater Research 1(1).
Cintron, G., and Y. Schaeffer-Novelli. 1981. Introduccion a la ecologia del manglar. Paper presented at Seminario sobre ordenacion y desarrollo integral de las zonas costeras, Guayaquil, Ecuador.
Cintron, G., and Y. Schaeffer-Novelli. 1984. Methods for studying mangrove structure. In *The mangrove ecosystem: research methods. Monographs on Oceanographic Methodology, Series 8*, ed. S. C. Snedaker and J. G. Snedaker, 91-113. Paris: UNESCO.
Cintron, G., A. E. Lugo, D. J. Pool, and G. Morris. 1978. Mangroves of arid environments in Puerto Rico and adjacent islands. *Biotropica* 10:110-121.
Clough, B.F., and P.M. Attiwill. 1982. Primary productivity of mangroves. In *Mangrove ecosystems in Australia: Structure, function and management. Proceedings of the Australian National Mangrove Workshop*, ed. B. F. Clough, 213-222. Canberra: Australian National Univ. Press.
Colin, P. L. 1976. Filter feeding and predation on the eggs of *Thalassoma* sp. by the scombrid fish *Rastrelliger kanagurta*. *Copeia* 1976:596-597.
Colin, P. L. 1978. *Caribbean Reef Invertebrates and Plants*. Neptune City: T.F.H. Publ. Inc. Ltd.
Collard, S., and C. D'Asaro. 1973. Benthic invertebrates of the eastern Gulf of Mexico. In *A summary of knowledge of the eastern Gulf of Mexico*, ed. J. Jones, R. Ring, M. Rinkel, and R. Smith, IIIG-1 to IIIG-27. St. Petersburg: State Univ. Sys. of Florida, Inst. of Oceanography.
Connell, J. H. 1978. Diversity in tropical rain forests and coral reefs. *Science* 199:1302-1310.
Conover, J. T. 1968. Importance of natural diffusion gradients and transport of substances related to benthic marine plant metabolism. *Bot. Mar.* 11(1-4):1-9.
Continental Shelf Associates, Inc. 1986. *Assessment of hurricane damage in the Florida Big Bend seagrass beds*. New Orleans: U.S. Department of the Interior, Minerals Management Service.
Continental Shelf Associates, Inc. 1987. *Southwest Florida shelf regional biological communities survey. Year 3 final report*. OCS Study MMS 86-0109. New Orleans: U.S. Department of the Interior, Minerals Management Service.
Continental Shelf Associates, Inc. 1989. *Southwest Florida nearshore benthic habitat study, narrative report*. OCS Study MMS 89-0080. New Orleans: U.S. Department of the Interior, Minerals Management Service.
Continental Shelf Associates, Inc. and Martel Laboratories, Inc. 1985. *Florida Big Bend seagrass habitat study narrative report*. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Cooksey, K. E., B. Cooksey, P. M. Evans, and E. L. Hildebrand. 1975. Benthic diatoms as contributors to the carbon cycle in a mangrove community. In *10th European Symposium on Marine Biology, Vol. 2.*, 165-178. Ostend, Belgium.

Courtenay, W. R., D. J. Herrema, M. J. Thompson, W. P. Azzinaro, and J. van Montfrans. 1974. *Ecological Monitoring of Beach Erosion Control Projects, Broward County, Florida, and Adjacent Areas.* Fort Belvoir, VA: U.S. Army Corps of Engineers, Coastal Engineering Research Center, Tech. Memo. 42.

Crossland, C. J. 1983. Dissolved nutrients in coral reef waters. In *Perspectives on coral reefs*, ed. D.J. Barnes, 56-68. Townsville, Queensland, Australia: Brian Clouston.

Cubit, J. D., C. D. Getter, J. B. C. Jackson, S. D. Garrity, H. M. Caffey, R. C. Thompson, E. Weil, and M. J. Marshall. 1987. An oil spill affecting coral reefs and mangroves on the Caribbean coast of Panama. In *Oil Spill Conference: Proceedings of the tenth biennial conference.* Washington, DC: American Petroleum Institute. API Publ. No. 4452.

Curtis, S. J. 1933. Working plan for the Sundarbans Division (1931-51). Forest Dept., Bengal.

Davis, G. E. 1979. *Outer continental shelf resource management map, coral distribution, Fort Jefferson National Monument, the Dry Tortugas.* New Orleans: U.S. National Park Service and Bureau of Land Management.

Davis, G. E. 1982. A century of natural change in coral distribution at the Dry Tortugas: A comparison of reef maps from 1881 and 1976. *Bull. Mar. Sci.* 32:608-623.

Davis, J. H., Jr. 1938. Mangroves - makers of land. *Nature* 31:551-553.

Davis, J. H., Jr. 1940. The ecology and geologic role of mangroves in Florida. *Carnegie Institution of Washington Publ. No.* 517:303-412. (*Papers from the Tortugas Lab., Vol. 32.*).

Dawes, C. J. 1985. Seasonal proximate constituents and caloric values in seagrasses and algae on the west coast of Florida. *J. Coast. Res.* 2:25-32.

Dawes, C. J. 1987. The dynamic seagrasses of the Gulf of Mexico and Florida coasts. In *Proceedings of the symposium on subtropical-tropical seagrasses of the southeastern United States*, ed. M. Durako, R. Phillips, and R. Lewis, 25-38. Florida Mar. Res. Publ. No. 42. St. Petersburg, FL.

Dawes, C. J., and J. M. Lawrence. 1980. Seasonal changes in the proximate constituents of the seagrasses, *Thalassia testudinum*, *Halodule wrightii*, and *Syringodium filiforme*. *Aquat. Bot.* 8:371-380.

Dawes, C. J., and J. M. Lawrence. 1983. Proximate composition and caloric content of seagrasses. *Mar. Technol. Soc. J.* 17(2):53-58.

Dawes, C. J., M. O. Hall, and R. K. Riechert. 1985. Seasonal biomass and energy content of seagrass communities on the west coast of Florida. *J. Coast. Res.* 1:255-262.

DeFelice, D. R., and G. W. Lynts. 1978. Benthic marine diatom associations: Upper Florida Bay and associated sounds. *J. Phycol.* 14(1):25-33.

DeLaune, R. D., C. N. Reddy, and W. H. Patrick, Jr. 1981. Accumulation of plant nutrients and heavy metals through sedimentation process and accretion in a Louisiana salt marsh. *Estuaries* 4:328-334.

Delesalle, B., R. Galzin, and B. Salvat, ed. 1985. *Proceedings, Fifth International Coral Reef Congress, Tahiti.* Six volumes. Moorea, French Polynesia: Antenne Museum-EPHE.

den Hartog, C. 1970. *The seagrasses of the world.* Amsterdam: North-Holland Publishing Co.

den Hartog, C. 1971. The dynamic aspect in the ecology of sea-grass communities. *Thalassia Jugosl.* 7(1):101-112.

den Hartog, C. 1977. Structure, function, and classification in seagrass communities. In *Seagrass ecosystems: A scientific perspective*, ed. C. McRoy and C. Helfferich, 89-122. New York: Marcel Dekker.

De Ruytor, V. S. E. D. 1984. The composition of algal vegetation in and outside damselfish territories on a Florida, USA reef. *Aquat. Bot.* 20:11-20.

Di Salvo, L. 1971. Ingestion and assimilation of bacteria by two scleractinian coral species. In *Experimental Coelenterate Biology*, ed. H. Lenhoff, L. Muscatine, and L. Davis, 129-136. Honolulu: Univ. of Hawaii Press.

Dost, H., ed. 1973. *Acid sulfate soils.* Publ. No. 18, Vols. I and II. Wageningen, Netherlands: International Institute for Land Reclamation and Improvement.

Ducklow, H. W., and R. Mitchell. 1979. Observations on naturally and artificially diseased tropical corals: A scanning electron microscope study. *Microb. Ecol.* 5:215-223.

Durako, M. J., and M. D. Moffler. 1981. Variation in *Thalassia testudinum* seedling growth related to geographic origin. In *Proceedings, 8th Annual Conference on Wetlands Restoration and Creation*, ed. R. H. Stovall, 99-117. Tampa: Hillsborough Community College.

Durako, M. J., and M. D. Moffler. 1985a. Observations on the reproductive ecology of *Thalassia testudinum* (Hydrocharitaceae) II. Leaf width as a secondary sex character. *Aquat. Bot.* 21:265-275.

Durako, M. J., and M. D. Moffler. 1985b. Observations on the reproductive ecology of *Thalassia testudinum* (Hydrocharitaceae). III. Spatial and temporal variations in reproductive patterns within a seagrass bed. *Aquat. Bot.* 22:265-276.

Durako, M. J., and M. D. Moffler. 1985c. Spatial influences on temporal variations in leaf growth and chemical composition of *Thalassia testudinum* Banks ex Konig in Tampa Bay, Florida. *Gulf Res. Rep.* 8:1:43-49.

Durako, M. J., R. C. Phillips, and R. R. Lewis III, ed. 1987. *Proceedings of the symposium on subtropical-tropical seagrasses of the southeastern United States.* Florida Marine Research Publ. No. 42. St. Petersburg: Florida Department of Natural Resources, Bureau of Marine Research.

Dustan, P. 1977a. Besieged reefs of Florida's Keys. *Nat. Hist.* 86:72-76.

Dustan, P. 1977b. Vitality of reef coral populations of Key Largo, Florida: recruitment and mortality. *Environ. Geol.* 2:51-58.

Dustan, P. 1985. Community structure of reef-building corals in the Florida Keys: Carysfort Reef, Key Largo and Long Key Reef, Dry Tortugas. *Atoll Res. Bull.* 228.

Dustan, P., and J. Halas. 1987. Changes in the reef-coral community of Carysfort Reef, Key Largo, Florida: 1974 to 1982. *Coral Reefs* 6:91-106.

Earle, S. A. 1972. Benthic algae and seagrasses. In *Serial atlas of the marine environments, folio 22. Algae of the Gulf of Mexico*, ed. V. C. Bushnell, 15-17 and 125-129. New York: American Geographic Society.

Ebbs, N. K., Jr. 1966. The coral inhabiting polychaetes of the northern Florida reef tract, Part I. *Bull. Mar. Sci.* 16:455-485.

Egler, F. E. 1952. Southeast saline Everglades vegetation, Florida, and its management. *Vegetatio* 3:213-265.

Environmental Science and Engineering, Inc., LGL Ecological Research Associates, Inc., and Continental Shelf Associates, Inc. 1987. *Southwest Florida shelf ecosystems study data synthesis.* OCS Study MMS 87-0023. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Fadlallah, Y. H. 1983. Sexual reproduction development and larval biology in scleractinian corals. A review. *Coral Reefs* 2:129-150.
Faulkner, D., and R. Chesher. 1979. *Living corals*. New York: Clarkson N. Potter, Inc.
Feingold, J. S. 1988. Ecological studies of a cyanobacterial infection on the Caribbean sea plume *Pseudopterogorgia acerosa* (Coelenterata: Octocorallia). In *Proceedings, Sixth International Coral Reef Symposium, Townsville*, 157-162. Queensland, Australia.
Fell, J. W., and I. M. Master. 1980. The association and potential role of fungi in mangrove detrital systems. *Bot. Mar.* 23:257-263.
Fell, J. W., R. C. Cefalu, I. M. Master, and A. S. Tallman. 1975. Microbial activities in the mangrove (*Rhizophora mangle*) leaf detrital system. In *Proceedings, International symposium on biology and management of mangroves, Vols. I and II*, ed. G. Walsh, S. Snedaker, and H. Teas, 661-679. Gainesville: Inst. Food Agric. Sci., Univ. Florida.
Fenchel, T., and T. H. Blackburn. 1979. *Bacteria and mineral cycling*. New York: Academic Press.
Florida Department of Natural Resources. 1974. *Florida Keys Coastal Zone Management Study*. Tallahassee: Florida Department of Natural Resources.
Fonseca, M. S., W. J. Kenworthy, and G. W. Thayer. 1981. *Transplanting of the seagrasses Zostera marina and Halodule wrightii for the stabilization of subtidal dredged materials*. Ann. Rep. Matl. Mar. Fish. Lab., Beaufort, to U.S. Army Corps of Engineers.
Frost, S. H. 1977. Cenozoic reef systems of Caribbean-Prospects for paleoecologic synthesis. In *Reefs and Related Carbonates-Ecology and Sedimentology*, ed. S. H. Frost, M. P. Weiss, and J. B. Saunders, 93-110. Tulsa: Am. Assoc. Pet. Geol. Stud. Geol. 4.
Fry, B. F. 1983. Leaf growth in the seagrass *Syringodium filiforme* Kutz. *Aquat. Bot.* 16:361-368.
Fry, B. F. 1984. $^{13}C/^{12}C$ ratios and the trophic importance of algae in Florida *Syringodium filiforme* seagrass meadows. *Mar. Biol.* 79:11-19.
Gallatin, M. H. et al. 1958. *Soil survey (detailed-reconnaissance) of Dade County, Florida*. USDA Series 1947, No. 4.
Gassman, N. J., and A. M. Szmant. 1989. The effect of bleaching on tissue composition and reproduction in the hermatypic coral *Montastraea annularis*. Paper read at the Association of Marine Laboratories of the Caribbean, 8-12 May 1989, at Mayaguez, Puerto Rico.
Genkel, P. A. 1963. On the ecology of the mangrove plant. In *Usizioligiya drevesnykh rastenii*, 223-232. Akad. Nauk SSR, Moscow. Referat. Zh., Biol. No. 7V151.
Getter, C. D., S. C. Snedaker, and M. S. Brown. 1980. *Assessment of biological damages at the Howard Star oil spill site, Hillsborough Bay and Tampa Bay, Florida*. Report to the Florida Department of Natural Resources, Tallahassee, FL.
Ghiold, J., and P. Enos. 1982. Carbonate production of the coral *Diploria labyrinthiformis* in South Florida patch reefs. *Mar. Geol.* 45:281-296.
Gill, A. M., and P. B. Tomlinson. 1971. Studies on the growth of red mangrove (*Rhizophora mangle* L.). 3. Phenology of the shoot. *Biotropica* 3(2):109-124.
Ginsburg, R. N., and N. P. James. 1973. British Honduras by submarine. *GeoTimes* 18(5):23-24.
Gittings, S. R. 1988. The recovery process in a mechanically damaged coral reef community. Ph.D. diss., Texas A&M Univ., College Station.
Gladfelter, E. 1982. Skeletal development in *Acropora cervicornis* I. Patterns of calcium carbonate accretion in the axial corallite. *Coral Reefs* 1:45-51.
Gladfelter, E. 1983. The role of Scleractinian corals in the trophodynamics of the reef ecosystem. In *Coral reefs, seagrass beds, and mangroves: Their interaction in the coastal zones of the Caribbean*, ed. J. Ogden and E. Gladfelter, 35-50. Montevideo, Uruguay: UNESCO Reps. Mar. Sci. 23.
Gladfelter, E. 1984. Skeletal development in *Acropora cervicornis* III. A comparison of linear extension and calcium carbonate accretion measured over a year. *Coral Reefs* 3:51-57.
Gladfelter, E. 1985. Metabolism, calcification and carbon production II. Organism-level studies. In *Proceedings, Fifth International Coral Reef Congress, Tahiti*, 4:527-539. Moorea, French Polynesia: Antenne Museum-EPHE.
Glynn, P. W. 1962. *Hermodice carunculata* and *Mithraculus sculptus*, two hermatypic coral predators. Paper read at 4th Meeting of the Association of Island Marine Laboratories of the Caribbean, 1962.
Glynn, P. W. 1964. Common marine invertebrate animals of the shallow waters of Puerto Rico. In *Historia Natural de Puerto Rico*, 12-20. Mayaguez, Puerto Rico: Univ. Puerto Rico.
Glynn, P. W. 1973. Aspects of the ecology of coral reefs in the western Atlantic region. In *Biology and geology of coral reefs*, ed. O. A. Jones and R. Endean, 2:271-324. New York: Academic Press.
Glynn, P. W. 1980. Defense by symbiotic crustacea of host corals elicited by chemical cues from predator. *Oecologia* 47:287-290.
Glynn, P. W. 1988. Coral bleaching and mortality in the tropical eastern Pacific during the 1982-83 El Nino warming event. In *Mass bleaching of coral reefs in the Caribbean: A research strategy*, ed. J. Ogden and R. Wicklund, 42-45. National Undersea Research Program Rep. 88-2.
Goldberg, W., P. L. McLaughlin, and L. Fisher. 1985. Long term effects of beach restoration in a coralline environment: impact on macrobenthic and infaunal communities. In *Proceedings, Fifth International Coral Reef Congress, Tahiti*, 2:150. Moorea, French Polynesia: Antenne Museum-EPHE.
Golley, F. B., H. T. Odum, and R. F. Wilson. 1962. The structure and metabolism of a Puerto Rican red mangrove forest in May. *Ecology* 43:9-19.
Golley, F. B., J. T. McGinnis, R. G. Clements, G. I. Child, and M. J. Duever. 1975. *Mineral cycling in a tropical moist forest ecosystem*. Athens: Univ. of Georgia Press.
Golubic, S., R. D. Perkins, and K. J. Lukas. 1975. Boring microorganisms in carbonate substrates. In *The Study of Trace Fossils*, ed. R. W. Frey, 229-260. New York: Springer-Verlag.
Gomez, E., C. Birkeland, R. Buddemeier, R. Johannes, J. Marsh, Jr., and R. Tsuda, ed. 1981. *Proceedings of the Fourth International Coral Reef Symposium*. 2 Volumes. Quezon City, Philippines: Paragon Printing Corp.
Goreau, T. F. 1959. The ecology of Jamaican coral reefs. I. Species composition and zonation. *Ecology* 40(1):67-90.
Goreau, T. F., and N. Goreau. 1959a. The physiology of skeleton formation in corals. I. A method for measuring the rate of calcium deposition by corals under different conditions. *Biol. Bull.* 116:59-75.
Goreau, T. F., and N. Goreau. 1959b. The physiology of skeleton formation in corals. II. Calcium deposition by hermatypic corals under various conditions in the reef. *Biol. Bull.* 117:239-250.

Goreau, T. F., and N. Goreau. 1960. The uptake and distribution of labelled carbon in reef building corals with and without zooxanthellae. *Science* 131:668-669.
Goreau, T. F., and W. D. Hartman. 1963. Boring sponges as controlling factors in the formation and maintenance of coral reefs. *Am. Assoc. Adv. Sci. Publ.* 75:25-54.
Goreau, T. F., and W. D. Hartman. 1966. Sponge: effect on the form of reef corals. *Science* 151:343-344.
Goreau, T. F., and L. Land. 1974. Forereef morphology and depositional processes, north Jamaica. In *Reefs in Time and Space*, ed. L. Laporte, 77-89. Tulsa: Soc. Econ. Paleontol. Mineral. Spec. Publ. No. 18.
Grassle, F. J. 1973. Variety in coral reef communities. In *Biology and geology of coral reefs*, ed. O. Jones and R. Endean, 2:247-270. New York: Academic Press.
Greenberg, I. 1977. *Guide to the corals and fishes of Florida, the Bahamas and the Caribbean*. Miami: Seahawk Press.
Greenway, M. 1976. The grazing of *Thalassia testudinum* in Kingston Harbour, Jamaica. *Aquat. Bot.* 2:117-126.
Grey, W. F., and M. D. Moffler. 1978. Flowering of the seagrass *Thalassia testudinum* (Hydrocharitaceae) in Tampa Bay, Florida. *Aquat. Bot.* 6:93-101.
Halas, J. 1985. A unique mooring system for reef management in the Key Largo National Marine Sanctuary. In *Proceedings, Fifth International Coral Reef Congress, Tahiti*, 4:237-242. Moorea, French Polynesia: Antenne Museum-EPHE.
Halas, J. F. 1988. An inventory of shipwrecks, groundings, and cultural marine resources within the Key Largo National Marine Sanctuary region: A preliminary report. NOAA Tech. Mem. No. NA87AA-H-CZ007.
Halas, J., J. Halas, and D. Kincaid. 1984. *Diving and Snorkeling Guide to the Florida Keys*. New York: Pisces Books.
Hallock, P. 1981. Algal symbiosis: A mathematical analysis. *Mar. Biol.* 62:249-255.
Hallock, P. 1988. The role of nutrient availability in bioerosion: Consequences to carbonate buildups. Palaeogeogr., Palaeoclimatol., Palaeoecol. 63:275-291.
Hallock, P., and W. Schlager. 1986. Nutrient excess and the demise of coral reefs and carbonate platforms. *Palaios* 1:389-398.
Hallock, P., A. C. Hine, G. A. Vargo, W. C. Jaap, and J. A. Elrod. 1988. Platforms of the Nicaraguan Rise: Examples of the sensitivity of carbonate sedimentation to excess trophic resources. *Geology* 16:1104-1107.
Hanisak, M. D., S. M. Blair, G. M. Burzycki, M. A. Samuel, and J. K. Reed. 1988. Macroalgal recruitment at the *Wellwood* grounding site, Molasses Reef, Florida, USA. In *Program Abstracts, Sixth International Coral Reef Symposium, Townsville*, 40. Queensland, Australia.
Hanson, K. J., and M. F. Poindexter. 1972. The solar irradiance environment of Florida coastal water during FLARE. NOAA Tech. Memo. ERL AOML 16:975-996.
Harbison, P. 1984. Regional variations in the distribution of trace metals in modern intertidal sediments of northern Spencer Gulf, South Australia. *Mar. Geol.* 61:221-247.
Harbison, P. 1986. Mangrove muds - a sink and a source for trace metals. *Mar. Pollut. Bull.* 17:246-250.
Harlin, M. M. 1971. Translocation between marine hosts and their epiphytic algae. *Plant Physiol.* 47(suppl.):41.
Harlin, M. M. 1975. Epiphyte-host relations in seagrass communities. *Aquat. Bot.* 1:125-131.
Harlin, M. M. 1980. Seagrass epiphytes. In *Handbook of seagrass biology-an ecosystem perspective*, ed. R. C. Phillips and C. P. McRoy, 117-151. New York: Garland STPM Press.
Harlin, M. M., and B. Thorne-Miller. 1981. Nutrient enrichment of seagrass beds in a Rhode Island coastal lagoon. *Mar. Biol.* 65:221-229.
Hartung, R., and G. W. Klingler. 1970. Concentration of DDT by sedimented polluting oil. *Environ. Sci. Technol.* 4(5):407-410.
Hayes, M. O., and E. R. Gundlach. 1979. *Coastal processes field manual for oil spill assessment*. Prepared for National Oceanic and Atmospheric Administration, Office of Marine Pollution Assessment, Boulder, CO, by Research Planning Institute, Columbia, SC.
Heald, E. J. 1971. *The production of organic detritus in a South Florida estuary*. Sea Grant Tech. Bull. No. 6. Coral Gables: Univ. of Miami.
Hein, F. J., and M. J. Risk. 1975. Bioerosion of coral heads: inner patch reefs, Florida reef tract. *Bull. Mar. Sci.* 25(1):133-138.
Hicks, D. B., and L. A. Burns. 1975. Mangrove metabolic response to alterations of natural freshwater drainage to southwestern Florida estuaries. In *Proceedings of International Symposium on Biology and Management of Mangroves, Vols. I and II*, ed. G. Walsh, S. Snedaker, and H. Teas, 238-255. Gainesville: Inst. Food Agric. Sci., Univ. of Florida.
Hoffmeister, J. E. 1974. *Land from the sea. The geologic story of South Florida*. Miami: Univ. Miami Press.
Hudson, J. H. 1977. Long-term bioerosion rates on a Florida reef: A new method. In *Proceedings, Third International Coral Reef Symposium, Miami*, 2:491-497. Miami: Rosenstiel School of Marine and Atmospheric Science, Univ. of Miami.
Hudson, J. H. 1981. Response of *Montastraea annularis*: A record of environmental change in Key Largo Coral Reef Marine Sanctuary, Florida. *Bull. Mar. Sci.* 31:444-459.
Hudson, J. H. 1984. A century of *Montastraea annularis* growth at Looe Key National Marine Sanctuary, Florida, USA. Paper read at Advances in Reef Science, a joint meeting of the Atlantic Reef Committee and the International Society for Reef Studies, 26-28 October, at Univ. of Miami, Miami, FL.
Hudson, J. H., and R. Diaz. 1989. Damage survey and restoration of M/V Wellwood grounding site, Molasses Reef, Key Largo National Marine Sanctuary, Florida. In *Proceedings, Sixth International Coral Reef Symposium, Townsville*. Queensland, Australia.
Hudson, J. H., E. Shinn, R. Halley, and B. Lidz. 1976. Sclerochronology: A tool for interpreting past environments. *Geology* 4:361-364.
Hudson, J. H., G. V. N. Powell, M. B. Robblee, and T. J. Smith III. 1989. A 107-year-old coral from Florida Bay: Barometer of natural and man-induced catastrophes? *Bull. Mar. Sci.* 44:283-291.
Humm, H. J. 1956. Seagrasses of the northern Gulf coast. *Bull. Mar. Sci. Gulf Caribb.* 4:305-308.
Humm, H. J. 1964. Epiphytes of the sea grass, *Thalassia testudinum*, in Florida. *Bull. Mar. Sci. Gulf Caribb.* 14(2):306-341.
Humm, H. J. 1969. A letter to Mr. John J. McCue. In *The structure of detritus-based food chains in a South Florida mangrove system*, W. E. Odum, 160-162. Ph.D. diss., Univ. of Miami.
Humm, H. J. 1973. Seagrasses. In *A summary of knowledge of the eastern Gulf of Mexico*, ed. J. F. Jones, R. E. Ring, M. O. Rinkel, and R. E. Smith, Section III-C. Orlando: Martin Marietta Aerospace.
Huston, M. 1985a. Variation in coral growth rates with depth at Discovery Bay, Jamaica. *Coral Reefs* 4:19-25.
Huston, M. 1985b. Patterns of species diversity on coral reefs. *Annu. Rev. Ecol. Syst.* 16:149-177.

Isa, Y., and K. Yamazato. 1984. The distribution of carbonic anhydrase in a staghorn coral *Acropora hebes* (Dana). *Galaxea* 3:25-36.
Iverson, R. L., and H. F. Bittaker. 1986. Seagrass distribution in the eastern Gulf of Mexico. *Estuar. Coast. Shelf Sci.* 22:577-602.
Jaap, W. C. 1979. Observations on zooxanthellae expulsion at Middle Sambo Reef, Florida Keys, USA. *Bull. Mar. Sci.* 29:414-422.
Jaap, W. C. 1981. Stony corals (Milleporina and Scleractinia). In *Key Largo Coral Reef National Marine Sanctuary Deep Water Resource Survey*, ed. S. Jameson, 7-13. Washington, DC: NOAA Tech. Rep. CZ/SP1.
Jaap, W. C. 1983. Population dynamics of stony corals in Biscayne National Park patch reefs, Florida, USA. Paper read at Colloque annuel of the International Society for reef studies, 8-9 December 1983, at Juan les Pins, France.
Jaap, W. C. 1984. *The ecology of the South Florida coral reefs: A community profile.* FWS/OBS-82/08. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.
Jaap, W. C. 1985. An epidemic zooxanthellae expulsion during 1983 in the lower Florida Keys coral reefs: Hyperthermic etiology. *Proceedings, Fifth International Coral Reef Congress, Tahiti*, 6:143-148. Moorea, French Polynesia: Antenne Museum-EPHE.
Jaap, W. C. 1988. The 1987 zooxanthellae expulsion event in Florida Reefs. In *Mass bleaching of coral reefs in the Caribbean: A research stratagy*, ed. J. C. Ogden and R. Wicklund, 24-29. Nat. Undersea Res. Prog. Rep. 88-2.
Jaap, W. C., and P. Hallock. In press. Reef Ecosystems. In *The Ecosystems of Florida*, ed. R. L. Myers and J. J. Ewel. Gainesville: Univ. Presses of Florida.
Jaap, W. C., W. G. Lyons, P. Dustan, and J. C. Halas. 1989. Stony coral (Scleractinia and Milleporina) community structure at Bird Key Reef, Ft. Jefferson National Monument, Dry Tortugas, Florida. *Fla. Mar. Res. Publ.* 46:1-31.
Jackson, J. B. C., and J. E. Winston. 1982. Ecology of cryptic coral reef communities. I. Distribution and abundance of major groups of encrusting organisms. *J. Exp. Mar. Biol. Ecol.* 57:135-147.
Jackson, J. B. C., J. D. Cubit, B. D. Keller, V. Batista, K. Burns, H. M. Caffey, R. L. Caldwell, S. D. Garrity, C. D. Getter, C. Gonzalez, H. M. Guzman, K. W. Kaufmann, A. H. Knap, S. C. Levings, M. J. Marshall, R. Steger, R. C. Thompson, and E. Weil. 1989. Ecological effects of a major oil spill on Panamanian coastal marine communities. *Science* 243:37-44.
James, N. P., and I. G. Macintyre. 1985. Carbonate depositional environments modern and ancient. Part 1: Zonation, depositional facies, and diagenesis. *Colo. Sch. Mines Q.* 80:1-70.
Jameson, S. C. 1981. *Key Largo Coral Reef National Marine Sanctuary deep water resource survey.* Washington, DC: NOAA Tech. Rep. CZ/SP1.
Jimenez, J. A., A. E. Lugo, and G. Cintron. 1985b. Tree mortality in mangrove forests. *Biotropica* 17:177-185.
Jimenez, J. A., R. Martinez, and L. Encarnacion. 1985a. Massive tree mortality in a Puerto Rican mangrove forest. *Caribb. J. Sci.* 21:75-78.
Jindrich, V. 1972. Biogenic buildups and carbonate sedimentation, Dry Tortugas reef complex, Florida. Ph.D. diss., State Univ. New York, Binghamton.
Johannes, R. E., W. J. Wiebe, and C. J. Crossland. 1983. Three patterns of nutrient flux in a coral reef community. *Mar. Ecol. Prog. Ser.* 12:105-111.
Jones, A. C., S. A. Berkeley, J. A. Bohnsack, S. A. Bortone, D. K. Camp, G. H. Darcy, J. C. Davis, K. D. Haddad, M. Y. Hedgepeth, E. W. Irby, Jr., W. C. Jaap, F. S. Kennedy, Jr., W. G. Lyons, E. L. Nakamura, T. W. Perkins, J. K. Reed, K. A. Steidinger, J. T. Tilmant, and R. O. Williams. 1986. Oceanic habitat and fishery resources of Florida. In *Florida aquatic habitat and fishery resources*, ed. W. Seaman, Jr., 437-542. Kissimmee: Am. Fish. Soc., Fla. Chapter.
Jones, J. A. 1963. Ecological studies of the southeastern Florida patch reefs. I: Diurnal and seasonal changes in the environment. *Bull. Mar. Sci. Gulf Caribb.* 13:282-307.
Jones, J. A. 1977. Morphology and development of Southeast Florida patch reefs. In *Proceedings, Third International Coral Reef Symposium, Miami*, 2:231-235. Miami: Rosenstiel School of Marine and Atmospheric Science, Univ. of Miami.
Jones, O., and R. Endean, ed. 1973-77. *Biology and geology of coral reefs*, Vol. 1-4. New York: Academic Press.
Kanwisher, J. W., and S. A. Wainwright. 1967. Oxygen balance in some reef corals. *Biol. Bull.* 133:378-390.
Kaplan, E. H. 1982. *A field guide to coral reefs of the Caribbean and Florida.* Peterson Field Guide Series No. 27. Boston: Houghton Mifflin Co.
Kaufman, L. 1977. The three spot damselfish: effects on benthic biota of Caribbean coral reefs. In *Proceedings, Third International Coral Reef Symposium, Miami*, 1:559-564. Miami: Rosenstiel School of Marine and Atmospheric Science, Univ. of Miami.
Kawaguti, S., and S. Sakumoto. 1948. The effect of light on the calcium deposition of corals. *Bull. Oceanogr. Inst. Taiwan* 4:65-70.
Khan, S. A. 1966. Working plan for the Coastal Zone Afforestation Division from 1963-64 to 1982-83. Government of West Pakistan. Agriculture Dep., Lahore.
Kikuchi, T. 1980. Faunal relationships in temperate seagrass beds. In *Handbook of seagrass biology - an ecosystem perspective*, ed. R. C. Phillips and C. P. McRoy, 152-172. New York: Garland STPM Press.
Kinsey, D. W. 1985. Metabolism, calcification and carbon production I. System level studies. In *Proceedings, Fifth International Coral Reef Congress, Tahiti*, 4:505-526. Moorea, French Polynesia: Antenne Museum-EPHE.
Kinzie, R. A. 1974. *Plexaura homomalla*: the biology and ecology of a harvestable marine resource. *Stud. Trop. Oceanogr.* 12:22-38.
Kissling, D. L. 1977. Population structure characteristics for some Paleozoic and modern corals. In *Proceedings, Second International Symposium on corals and fossil coral reefs*, 457-507. Paris: Bureau du Recherches Geologiques et Mineres.
Kissling, D. L., and G. Taylor. 1977. Habitat factors for reef-dwelling ophiurids in the Florida Keys. In *Proceedings, Third International Coral Reef Symposium, Miami*, 1:225-231. Miami: Rosenstiel School of Marine and Atmospheric Science, Univ. of Miami.
Kluge, M. 1976. Carbon and nitrogen metabolism under water stress. In *Water and plant life, problems and modern approaches*, ed. O. L. Lange, L. Kappen, and E.-D. Schulze, 243-252. Ecological Studies No. 19. New York: Springer-Verlag.

Kojis, B., and N. Quinn. 1984. Puberty in corals: An examination of Connell's hypotheses. Paper read at Advances in Reef Science, a joint meeting of the Atlantic Reef Committee and the International Society for Reef Studies, 26-28 October, at The Univ. of Miami, Miami, FL.

Kylin, A., and R. S. Quatrano. 1975. Metabolic and biochemical aspects of salt tolerance. In *Plants in saline environments*, ed. A. Poljakoff-Mayber and J. Gale, 147-167. Ecological Studies No. 15. New York: Springer-Verlag.

Lahmann, E. J. 1988. Effect of different hydrological regimes on the productivity of *Rhizophora mangle* L.: A case study of mosquito control impoundments at Hutchinson Island, St. Lucie County, Florida. Ph.D. diss., Univ. of Miami.

Landon, S. 1975. Environmental controls on growth rates in hermatypic corals from the Lower Florida Keys. M.S. thesis, State Univ. New York, Binghamton.

Lang, J. 1971. Interspecific aggression by Scleractinian corals. I. The rediscovery of *Scolymia cubensis* (Milne, Edwards and Haime). *Bull. Mar. Sci.* 21:952-959.

Lang, J. 1973. Interspecific aggression by scleractinian coral 2. Why the race is not to the swift. *Bull. Mar. Sci.* 23:260-279.

Lang, J. 1974. Biological zonation at the base of a reef. *Am. Sci.* 62(3):272-281.

Lapointe, B. E., and N. P. Smith. 1987. *A preliminary investigation of upwelling as a source of nutrients to Looe Key National Marine Sanctuary*. Washington, DC: NOAA Tech. Memo. No. 9.

Lapointe, B. E., and J. O'Connell. 1988. *The effects of on-site sewage disposal systems on nutrient relations of groundwaters and nearshore waters of the Florida Keys*. Key West: Tech. Rep., Monroe County Planning Department.

Lassuy, D. R. 1983. Species profiles: Life histories and environmental requirements (Gulf of Mexico)--spotted seatrout. FWS/OBS-82/11.4. Washington, DC: U.S. Fish and Wildlife Service, Division of Biological Services.

Lee, T. N. 1989. *Physical oceanography literature review of the Straits of Florida and eastern Gulf of Mexico.* Unpubl. manuscript.

Lessios, H., D. Robertson, and L. Cubit. 1984b. Spread of *Diadema* mass mortality through the Caribbean. *Science* 226:335-337.

Lessios, H., J. Cubit, D. Robertson, M. Shulman, M. Parker, S. Garrity, and S. Levings. 1984a. Mass mortality of *Diadema antillarum* on the Caribbean coast of Panama. *Coral Reefs* 4:173-182.

Lewis, J. B. 1977. Processes of organic production on coral reefs. *Biol. Rev.* 52:305-347.

Lewis, R. R., and R. C. Phillips. 1981. Occurrence of seeds and seedlings of *Thalassia testudinum* Banks ex Konig in the Florida Keys (U.S.A.). *Aquat. Bot.* 9:377-380.

Lewis, R. R., M. J. Durako, M. D. Moffler, and R. C. Phillips. 1985a. Seagrass meadows of Tampa Bay - a review. In *Proceedings, Tampa Bay area scientific information symposium*, ed. S. F. Treat, J. L. Simon, R. R. Lewis, and R. L. Whitman, 216-246. Florida Sea Grant Publ. No. 65. Minneapolis: Burgess Publ. Co.

Lewis, R. R., R. G. Gilmore, D. W. Crewz, and W. E. Odum. 1985b. Mangrove habitat and fishery resources of Florida. In *Florida aquatic habitat and fishery resources*, ed. W. Seaman, Jr., 281-336. Kissimmee, FL: Florida Chapter of the American Fisheries Society.

Limbaugh, C. 1961. Cleaning symbiosis. *Sci. Am.* 205:42-49.

Littler, M. M., D. S. Littler, and B. E. Lapointe. 1986. *Baseline studies of herbivory and eutrophication on dominant reef communities of Looe Key National Marine Sanctuary*. Washington, DC: NOAA Tech. Memo. No. 1.

Livingston, R. J. 1987. Historic trends of human impacts on seagrass meadows in the southeastern United States. In *Proceedings of the symposium on subtropical-tropical seagrasses of the southeastern United States*, ed. M. Durako, R. Phillips, and R. Lewis, 139-152. Florida Mar. Res. Publ. No. 42. St. Petersburg, FL.

Lizama, J., and R. Blanquet. 1975. Predation on sea anemones by the amphinomid polychaete *Hermodice carunculata*. *Bull. Mar. Sci.* 25:442-443.

Longley, W. H., and S. F. Hildebrand. 1941. Systematic catalogue of the fishes of Tortugas, Fla. with observations on color, habits and local distribution. *Pap. Tortugas Lab.* 34:1-331.

Lot-Helgueras, A., C. Vazquez-Yanes, and F. Menendez. 1975. Physiognomic and floristic changes near the northern limit of mangroves in the Gulf coast of Mexico. In *Proceedings of International Symposium on Biology and Management of Mangroves, Vols. I and II*, ed. G. Walsh, S. Snedaker, and H. Teas, 52-61. Gainesville: Inst. Food Agric. Sci., Univ. of Florida.

Lowe, E. F., and J. M. Lawrence. 1976. Absorption efficiencies of *Lytechinus variegatus* (Lamarck) (Echinodermata) for selected marine plants. *J. Exp. Mar. Biol. Ecol.* 21:223-234.

Loya, J. 1972. Community structure and species diversity of hermatypic corals at Eilat, Red Sea. *Mar. Biol.* 13:100-123.

Lu, J. C. S., and K. Y. Chen. 1977. Migration of trace metals in interfaces of seawater and polluted surficial sediments under different redox conditions. *Environ. Sci. Technol.* 11:174-182.

Lugo, A. E., and C. Patterson-Zucca. 1977. The impact of low temperature stress on mangrove structure and growth. *Trop. Ecol.* 18(2):149-161.

Lugo, A. E., and S. C. Snedaker. 1974. The ecology of mangroves. *Annu. Rev. Ecol. Syst.* 5:39-64.

Lugo, A. E., G. Cintron, and C. Goenaga. 1981. Mangrove ecosystems under stress. In *Stress effects on natural ecosystems*, ed. G.W. Barrett and R. Rosenberg, 129-153. London: John Wiley & Sons Ltd.

Lugo, A. E., G. Evink, M. Brinson, A. Broce, and S. C. Snedaker. 1975. Diurnal rates of photosynthesis, respiration and transpiration in mangrove forests of South Florida. In *Tropical ecological systems, ecological studies, Vol. II.*, ed. F. B. Golley and E. Medina, 335-350. New York: Springer-Verlag.

Lyons, W. G., D. Barber, S. Foster, F. Kennedy, and G. Milano. 1981. The spiny lobster, *Panulirus argus*, in the Middle and Upper Florida Keys: Population Structure, Seasonal Dynamics, and Reproduction." *Fla. Mar. Res. Publ.* 38:1-38.

Macnae, W. 1966. Mangroves in eastern and southern Australia. *Aust. J. Bot.* 14:67-104.

Margalef, R. 1968. The pelagic ecosystem of the Caribbean Sea. In *Symposium on Investigations and Resources of the Caribbean Sea and Adjacent Regions*, 484-498. Paris: UNESCO.

Marsden, J. R. 1960. Polychaetous annelids from the shallow waters around Barbados and other islands of the West Indies, with notes on larval forms. *Can. J. Zool.* 38:989-1020.

Marsden, J. R. 1962. A coral-eating polychaete. *Nature* 193:598.

Marszalek, D., G. Babashoff, M. Noel, and P. Worley. 1977. Reef distribution in South Florida. In *Proceedings, Third International Coral Reef Symposium, Miami* 2:223-230. Miami: Rosenstiel School of Marine and Atmospheric Science, Univ. of Miami.
Martosubroto, P., and N. Naamin. 1977. Relationship between tidal forests (mangroves) and commercial shrimp production in Indonesia. *Mar. Res. Indones.* 18:81-86.
Marx, J. M., and W. F. Herrnkind. 1985. Macroalgae (Rhodophyta: *Laurencia* spp.) as habitat for young juvenile lobsters, *Panulirus argus*. *Bull. Mar. Sci.* 36(3):423-431.
Mayer, A. 1902. The Tortugas as a station for research in biology. *Science* 17:190-192.
Mayer, A. 1914. The effects of temperature upon tropical marine animals. *Pap. Tortugas Lab.* 6:1-14.
McMahan, C. A. 1968. Biomass and salinity tolerance of shoalgrass and manatee grass in lower Laguna Madre, Texas. *J. Wildl. Manage.* 33:501-506.
McMillan, C. 1974. Salt tolerance of mangroves and submerged aquatic plants. In *Ecology of halophytes*, ed. R. J. Reimold and W. H. Queen, 379-390. New York: Academic Press.
McMillan, C. 1978. Morphogeographic variation under controlled circumstances in five seagrasses: *Thalassia testudinum*, *Halodule wrightii*, *Syringodium filiforme*, *Halophila engelmanni*, and *Zostera marina*. *Aquat. Bot.* 4:169-189.
McMillan, C. 1979. Differentiation in response to chilling temperatures among populations of three marine spermatophytes, *Thalassia testudinum*, *Syringodium filiforme*, and *Halodule wrightii*. *Am. J. Bot.* 66:810-819.
McMillan, C. 1981. Seed reserves and seed germination for two seagrasses, *Halodule wrightii* and *Syringodium filiforme*, from the western Atlantic. *Aquat. Bot.* 11:279-296.
McMillan, C. 1982. Reproductive physiology of tropical seagrasses. *Aquat. Bot.* 14:245-258.
McMillan, C. 1983. Seed germination in *Halodule wrightii* and *Syringodium filiforme* from Texas and the U.S. Virgin Islands. *Aquat. Bot.* 15:217-220.
McMillan, C., and F. N. Moseley. 1967. Salinity tolerances of five marine spermatophytes of Redfish Bay, Texas. *Ecology* 48:503-506.
McMillan, C., and R. C. Phillips. 1979. Differentiation in habitat response among populations of new world seagrasses. *Aquat. Bot.* 7:185-196.
McRoy, C. P., and J. J. Goering. 1974. Nutrient transfer between the seagrass *Zostera marina* and its epiphytes. *Nature* 248(5444):173-174.
McRoy, C. P., and C. Helfferich. 1980. Applied aspects of seagrasses. In *Handbook of seagrass biology - an ecosystem approach*, ed. R. C. Phillips and C. P. McRoy, 297-342. New York: Garland Publications Inc.
McRoy, C. P., and C. McMillan. 1977. Production ecology and physiology of seagrasses. In *Seagrass ecosystems: A scientific perspective*, ed. C. P. McRoy and C. Helfferich, Chapter 3. New York: Marcel Dekker.
McRoy, C. P., R. J. Barsdate, and M. Nebert. 1972. Phosphorous cycling in an eelgrass (*Zostera marina* L.) ecosystem. *Limnol. Oceanogr.* 17:58-67.
Mergner, H. 1977. Hydroids as indicator species for ecological parameters in Caribbean and Red Sea coral reefs. In *Proceedings, Third International Coral Reef Symposium, Miami* 2:119-126. Miami: Rosenstiel School of Marine and Atmospheric Science, Univ. of Miami.
Meyer, J. L., E. T. Schulte, and G. S. Helfman. 1983. Fish schools: An asset to corals. *Science* 220:1047-1049.
Miller, J., ed. 1988. *Results of a workshop on coral reef research and management in the Florida Keys: A blueprint for action*. Rockville: Nat. Undersea Res. Prog. Res. Rep. 88-5.
Mitchell, R., and I. Chet. 1975. Bacterial attack of corals in polluted seawater. *Microb. Ecol.* 2:227-233.
Mizrachi, D., R. Pannier, and F. Pannier. 1980. Assessment of salt resistance mechanisms as determinant physio-ecological parameters of zonal distribution of mangrove species. I. Effect of salinity stress on nitrogen metabolism balance and protein synthesis in the mangrove species *Rhizophora mangle* and *Avicennia nitida*. *Bot. Mar.* 23:289-296.
Moe, M. A., Jr. 1963. *A Survey of Offshore Fishing in Florida*. St. Petersburg: Florida State Board of Conservation, Marine Laboratory, Prof. Pap. Ser. No. 4:1-117.
Moffler, M. D., and M. J. Durako. 1987. Reproductive biology of the tropical-subtropical seagrasses of the United States. In *Proceedings of the symposium on subtropical-tropical seagrasses of the southeastern United States*, ed. M. Durako, R. Phillips, and R. Lewis, 77-88. Florida Mar. Res. Publ. No. 42. St. Petersburg, FL.
Moffler, M. D., M. J. Durako, and W. F. Grey. 1981. Observations on the reproductive ecology of *Thalassia testudinum* (Hydrocharitaceae). *Aquat. Bot.* 10:183-187.
Moore, D., and H. Bullis Jr. 1960. A deep-water coral reef in the Gulf of Mexico. *Bull. Mar. Sci. Gulf Caribb.* 10:125-128.
Morse, J. W., J. DeKanel, and K. Harris. 1979. Dissolution kinetics of synthetic aragonite and pteropod tests. *Am. J. Sci.* 279:488-502.
Mucci, A. 1986. Growth kinetics and composition of magnesian calcite overgrowths precipitated from seawater: Quantitative influence of orthophosphate ions. *Geochim. Cosmochim. Acta* 50:2255-2265.
Mukudan, C., and C. S. G. Pillai, ed. 1972. *Symposium on corals and coral reefs*. Cochin, India: The Marine Biological Association of India.
Multer, H. G. 1971. *Field guide to some carbonate rock environments. Florida Keys and western Bahamas*. Madison: Fairleigh Dickinson Univ.
Murali, R. S. 1982. Zero-energy coast. In *The encyclopedia of beaches and coastal environments*, ed. M. L. Schwartz, 883. Stroudsburg: Hutchinson Ross Publ.
Muscatine, L. 1980. Productivity of zooxanthellae. In *Primary Productivity in the Sea*, ed. P. Falkowski, 381-402. New York: Plenum Publ. Corp.
Muscatine, L., and J. W. Porter. 1977. Reef corals: mutualistic symbiosis adapted to nutrient-poor environments. *BioScience* 27:454-460.
National Academy of Sciences. 1974. *The effects of herbicides in South Vietnam. Part A. Summary and conclusions*. Washington, DC: National Academy Press.
Neumann, A. C. 1966. Observations on coastal erosion in Bermuda and measurements of the boring rate of the sponge, *Cliona lampa*. *Limnol. Oceanogr.* 11:92-108.
Neumann, A. C., and M. Ball. 1970. Submersible observations in the Straits of Florida: geology and bottom currents. *Bull. Geol. Soc. Am.* 81:2861-2874.
Neumann, A. C., J. Kofoed, and G. Keller. 1977. Lithoherms in the Straits of Florida. *Geology* 5:4-10.
Newbould, P. J. 1967. *Methods for estimating the primary production of forests. IBP Handbook No. 2*. Oxford: Blackwell Scientific.

Nobel, P. S. 1980. Leaf anatomy and water use efficiency. In *Adaptation of plants to water and high temperature stress*, ed. N. C. Turner and P. J. Kramer. New York: John Wiley and Sons.
Odum, H. T. 1963. Productivity measurements in Texas turtle grass and the effects of dredging an intracoastal channel. *Publ. Inst. Mar. Sci. Tex.* 9:48-58.
Odum, W. E. 1969. The structure of detritus-based food chains in a South Florida mangrove system. Ph.D. diss., Univ. of Miami.
Odum, W. E. 1970. Utilization of the direct grazing and plant detritus food chains by the striped mullet *Mugil cephalus*. In *Proceedings, Symposium on Marine Food Chains*, ed. J. Steele, 222-240.
Odum, W. E. 1971. *Pathways of energy flow in a South Florida estuary*. Sea Grant Tech. Bull. No. 7. Coral Gables: Univ. of Miami.
Odum, W. E., and R. E. Johannes. 1975. The response of mangroves to man-induced environmental stress. In *Tropical marine pollution*, ed. E. J. Ferguson-Wood and R. E. Johannes, 52-62. Elsevier Oceanography Series No. 12. Amsterdam: Elsevier Scientific Publ. Co.
Odum, W. E., C. C. McIvor, and T. J. Smith, III. 1982. *The ecology of mangroves of South Florida: A community profile*. FWS/OBS-81/24. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.
Odum, W. E., J. C. Zieman, and E. J. Heald. 1973. The importance of vascular plant detritus to estuaries. In *Proceedings of the Second Coastal Marsh and Estuary Management Symposium*, 91-114. Baton Rouge: Louisiana State Univ. Press.
Ogden, J. C. 1980. Faunal relationships in Caribbean seagrass beds. In *Handbook of seagrass biology: An ecosystem perspective*, ed. R. C. Phillips and C. P. McRoy, 173-198. New York: Garland STPM.
Ogden, J. C., and P. Lobel. 1978. The role of herbivorous fishes and urchins in coral reef communities. *Environ. Biol. Fish.* 3:49-63.
Opresko, D. 1973. Abundance and distribution of shallow-water gorgonians in the area of Miami, Florida. *Bull. Mar. Sci.* 23:535-558.
Orians, G. H., and E. W. Pfeiffer. 1970. Ecological effects of the war in Vietnam. *Science* 168:544-554.
Orpurt, P. R., and L. L. Boral. 1964. The flowers, fruits and seeds of *Thalassia testudinum* Konig. *Bull. Mar. Sci.* 14:296-302.
Orth, R. J., and J. van Montfrans. 1984. Epiphyte-seagrass relationships with an emphasis on the role of micrograzing: A review. *Aquat. Bot.* 18:43-69.
Ott, B., and J. Lewis, Jr. 1972. The importance of the gastropod *Coralliophila abbreviata* (Lamarck) and the polychaete *Hermodice carunculata* (Pallas) as coral reef predators. *Can. J. Zool.* 50:1651-1656.
Pannier, F., and R. F. Pannier. 1977. Interpretacion fisioecologica de la distribucion de manglares en las costas del continente suramericano. *Interciencia* 2(3):153-162.
Patriquin, D. G. 1972. The origin of nitrogen and phosphorus for growth of the marine angiosperm *Thalassia testudinum*. *Mar. Biol.* 15:35-46.
Patriquin, D. G. 1975. "Migration" of blowouts in seagrass beds at Barbados and Cariacou, West Indies, and its ecological and geological implications. *Aquat. Bot.* 1:163-189.
Patriquin, D. G., and R. Knowles. 1972. Nitrogen fixation in the rhizosphere of marine angiosperms. *Mar. Biol.* 16:49-58.
Patton, W. K. 1967. Studies on *Domecia acanthophora*, a commensal crab from Puerto Rico, with particular reference to modifications of the coral host and feeding habits. *Biol. Bull.* 132:56-67.
Patton, W. K. 1976. Animal associates of living reef corals. In *Biology and geology of coral reefs*, ed. O. A. Jones and R. Endean, 3:1-36. New York: Academic Press.
Pearson, R. 1981. Recovery and recolonization of coral reefs. *Mar. Ecol. Prog. Ser.* 4:105-122.
Peters, E. 1984. A survey of cellular reactions to environmental stress and disease in Caribbean Scleractinian corals. *Helgol. wiss. Meeresunters.* 37:113-138.
Peters, E. C., J. C. Halas, and H. D. McCarty. 1986. Calicoblastic neoplasms in *Acropora palmata*, with a review of reports on anomalies of growth and form in corals. *J. Natl. Cancer Inst.* 76:895-912.
Peters, E., J. Oprandy, and P. Yevich. 1983. Possible causal agent of "white band disease" in Caribbean acroporid corals. *J. Invertebr. Pathol.* 41:394-396.
Petersen, C. J. G. 1918. The sea bottom and its production of fish food: A summary of the work done in connection with the valuation of Danish waters from 1883 to 1917. *Rep. Danske Biol. Stat.* 25:1-82.
Peterson, P. J., M. A. S. Burton, M. Gregson, S. M. Nye, and E. K. Porter. 1979. Accumulation of tin by mangrove species in West Malaysia. *Sci. Total Environ.* 11:213-221.
Phillips, R. C. 1960. *Observations on the ecology and distribution of the Florida seagrasses*. Florida State Bd. Conserv. Mar. Lab. Prof. Pap. Ser. No. 2. St. Petersburg, FL.
Phillips, R. C. 1962. *Distribution of seagrasses in Tampa Bay, Florida*. Florida State Bd. Conserv. Mar. Lab., Spec. Sci. Rep. No. 6. St. Petersburg, FL.
Pilson, M. E. Q., and S. B. Betzer. 1973. Phosphorus flux across a coral reef. *Ecology* 54:581-588.
Pool, D. J., A. E. Lugo, and S. C. Snedaker. 1975. Litter production in mangrove forests of southern Florida and Puerto Rico. In *Proceedings of International Symposium on Biology and Management of Mangroves, Vols. I and II*, ed. G. Walsh, S. Snedaker, and H. Teas, 213-237. Gainesville: Inst. Food Agric. Sci., Univ. of Florida.
Pool, D. J., S. C. Snedaker, and A. E. Lugo. 1977. Structure of mangrove forests in Florida, Puerto Rico, Mexico and Costa Rica. *Biotropica* 9(3):195-212.
Popp, M., and J. Polania. (no date). Compatible solutes in different organs of mangrove trees. Unpubl. manuscript.
Porter, J. W. 1987. Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (South Florida): Reef-building corals. U.S. Fish Wildl. Serv. Biol. Rep. 82(11.73).
Porter J. W., L. Muscatine, Z. Dubinski, and P. Falkowski. 1984. Primary production and photoadaptation in light and shade-adapted colonies of the symbiotic coral, *Stylophora pistillata*. *Proc. R. Soc. Lond.* 222B:161-180.
Powell, G. V. N., W. J. Kenworthy, and J. W. Fourqurean. 1989. Experimental evidence for nutrient limitation of seagrass growth in a tropical estuary with restricted circulation. *Bull. Mar. Sci.* 44:324-340.
Pulich, W. M., Jr. 1985. Seasonal growth dynamics of *Ruppia marina* L.s.l. and *Halodule wrightii* Aschers. in southern Texas and evaluation of sediment fertility status. *Aquat. Bot.* 23:53-66.
Ramos, H. 1983. Lower marine fungus associated with the black line disease in star coral *Montastraea annularis*. *Biol. Bull.* 165(2):429-435.

Randall, J. E. 1965. Grazing effect on sea grasses by herbivorous reef fishes in the West Indies. *Ecology* 46:255-260.
Randall, J. E., R. E. Schroeder, and W. A. Starck II. 1964. Notes on the biology of the echinoid *Diadema antillarum*. *Caribb. J. Sci.* 4:421-433.
Reed, J. K. 1985. Deepest distribution of Atlantic hermatypic corals. In *Proceedings, Fifth International Coral Reef Congress, Tahiti*, 6:249-254. Moorea, French Polynesia: Antenne Museum-EPHE.
Reid, G. K., Jr. 1954. An ecological study of the Gulf of Mexico fishes, in the vicinity of Cedar Key Florida. *Bull. Mar. Sci. Gulf Caribb.* 4(1):1-91.
Richardson, C., P. Dustan, and J. Lang. 1979. Maintenance of living space by sweeper tentacles of *Montastraea cavernosa*, a Caribbean reef coral. *Mar. Biol.* 55:181-186.
Risk, M. J., and J. K. MacGeachy. 1978. Aspects of bioerosion of modern Caribbean reefs. *Revta. Biol. Trop.* 26(Suppl. 1):85-105.
Roberts, H. H., L. J. Rouse, Jr., N. D. Walker, and H. Hudson. 1982. Cold water stress in Florida Bay and northern Bahamas: A product of winter frontal passages. *J. Sediment. Petrol.* 52:145-155.
Robertson, R. 1970. Review of the predators and parasites of stony corals, with special reference to symbiotic prosobranch gastropods. *Pac. Sci.* 24:43-54.
Roessler, M. 1965. An analysis of the variability of fish populations taken by otter trawl in Biscayne Bay, Florida. *Trans. Am. Fish. Soc.* 94:311-318.
Roessler, M. A., D. C. Tabb, R. Rehrer, and J. Garcia. 1974. Studies of effects of thermal pollution in Biscayne Bay, Florida. *Proc. Gulf Caribb. Fish. Inst.* 22:136-145.
Rollet, B. 1981. *Bibliography on mangrove research 1600-1975*. Paris: UNESCO.
Rose, C. R., and M. J. Risk. 1985. Increase in *Cliona delitrix* infestation of *Montastrea cavernosa* heads on an organically polluted portion of the Grand Cayman fringing reef. *Mar. Ecol.* 6:345-363.
Rosenfeld, J. K. 1979. Interstitial water and sediment chemistry of two cores from Florida Bay. *J. Sediment. Petrol.* 49:3:989-994.
Rützler, K., and D. Santavy. 1983. The black band disease of Atlantic reef corals. I. Description of the Cyanophyte pathogen. *Mar. Ecol.* 4(4):301-319.
Rützler, K., D. Santavy, and A. Antonius. 1983. The black band disease in Atlantic reef corals. III. Distribution, ecology, and development. *Mar. Ecol.* 4(4):329-358.
Sammarco, P. W. 1980. *Diadema* and its relationship to coral spat mortality: grazing, competition, and biological disturbance. *J. Exp. Mar. Biol. Ecol.* 45:245-272.
Sammarco, P. W., J. Levinton, and J. Ogden. 1974. Grazing and control of coral reef community structure by *Diadema antillarum* Philippi (Echinodermata: Echinoidea): A preliminary study. *J. Mar. Res.* 32:47-53.
Sand-Jensen, K. 1977. Effect of epiphytes on eelgrass photosynthesis. *Aquat. Bot.* 3:55-63.
Schmahl, G. P. 1984. Sponges. In *The ecology of the South Florida coral reefs: A community profile*, ed. W.C. Jaap, 37-40. U.S. Fish and Wildlife Serv. FWS/OBS 82/08.
Scholander, P. F. 1968. How mangrove desalinate water. *Physiol. Plant.* 21:251-261.
Scholander, P. F., H. T. Hammel, E. A. Hemmingsen, and E. D. Bradstreet. 1964. Hydrostatic pressure and osmotic potential in leaves of mangroves and some other plants. *Proc. Natl. Acad. Sci. U.S.A.* 52:119-125.
Scholl, P. W., F. C. Craighead, Sr., and M. Stuiver. 1969. Florida submergent curve revised: Its relation to coastal sedimentation rates. *Science* 163:562-564.
Schomer, N. S., and R. D. Drew. 1982. *An ecological characterization of the lower Everglades, Florida Bay, and Florida Keys*. U.S. Fish and Wildl. Serv. Biol. Serv. Program FWS/OBS-82/58.1.
Seba, D. B., and E. F. Corcoran. 1969. Surface slicks as concentrator of pesticides in the marine environment. *Pestic. Monit. J.* 3(3):190-193.
Shinn, E. A. 1963. Spur and groove formation on the Florida Reef tract. *J. Sediment. Petrol.* 33:291-303.
Shinn, E. A. 1966. Coral growth rate - an environmental indicator. *J. Paleontol.* 40:233-240.
Shinn, E. A. 1976. Coral reef recovery in Florida and the Persian Gulf. *Environ. Geol.* 1:241-254.
Shinn, E. A. 1980. Geologic history of Grecian Rocks, Key Largo Coral Reef Marine Sanctuary. *Bull. Mar. Sci.* 30:646-656.
Shinn, E. A. 1984. Geologic history, sediment, and geomorphic variations within the Florida reef tract. Paper read at Advances in Reef Science, a joint meeting of the Atlantic Reef Committee and the International Society for Reef Studies, 26-28 October, Univ. of Miami, Miami, FL.
Shinn, E. A. 1988. The geology of the Florida Keys. *Sea Front.* 34:46-53.
Shinn, E. A., J. H. Hudson, D. M. Robin, and B. Lidz. 1981. Spur and grooves revisited: construction versus erosion. In *Proceedings of the Fourth International Coral Reef Symposium*. 1:475-484. Quezon City, Philippines: Paragon Printing Corp.
Shinn, E. A., B. H. Lidz, J. L. Kindinger, and J. H. Hudson. 1989. *A field guide: Reefs of Florida and the Dry Tortugas*. Washington, DC: The 28th International Geological Congress.
Simkiss, K. 1964. Phosphates as crystal poisons of calcification: *Biol. Rev.* 39:487-505.
Skinner, R. H., and E. F. Corcoran. 1989. *John Pennekamp Coral Reef State Park: Assessment of water quality data from five stations. Vol.1, Nov. 1982 through Dec. 1984*. Tallahassee: Florida Department of Natural Resources.
Smith, C. L., and J. C. Tyler. 1975. Succession and stability in fish communities of dome-shaped patch reefs in the West Indies. *Am. Mus. Novit.* 2572:1-18.
Smith, H. 1897. Florida commercial sponges. *Bull. U.S. Fish Commer.* 17:225-240.
Smith, S. V., W. J. Kimmerer, E. A. Laws, R. E. Brock, and T. W. Walsh. 1981. Kaneohe Bay Sewage diversion experiment: Perspectives on ecosystem responses to nutritional perturbation. *Pac. Sci.* 35:279-395.
Smith, T. J. III, J. H. Hudson, M. B. Robblee, G. V. N. Powell, and P. J. Isdale. 1989. Freshwater flow from the Everglades to Florida Bay: A historical reconstruction based on fluorescent banding in the coral *Solenastrea bournoni*. *Bull. Mar. Sci.* 44:274-282.
Snedaker, S. C. 1982. Mangrove species zonation: Why? In *Tasks for vegetation science, Vol. 2. Contributions to the ecology of halophytes*, ed. D. N. Sen and K. S. Rjpurohit, 111-125. The Hague: Dr. W. Junk Publishers.
Snedaker, S. C. 1984. Mangroves: A summary of knowledge with emphasis on Pakistan. In *Marine geology and oceanography of Arabian Sea and coastal Pakistan*, ed. B. U. Haq and J. D. Milliman, 255-262. New York: Van Nostrand Reinhold Co.
Snedaker, S. C. 1989. Overview of ecology of mangroves and information needs for Florida Bay. *Bull. Mar. Sci.* 44(1):341-347.
Snedaker, S. C., and M. S. Brown. 1981. *Water quality and mangrove ecosystem dynamics*. EPA-600/4-81-022. Gulf Breeze, FL: U.S. Environmental Protection Agency, Environmental Research Laboratory.

Snedaker, S. C., and M. S. Brown. 1982. Primary productivity of mangroves. In *CRC handbook of biosolar resources, Vol. I, Pt. 2. Basic principles*, ed. A. Mitsui and C. C. Black, 477-485. Boca Raton: CRC Press.
Snedaker, S. C., and C. D. Getter. 1985. *Coasts: Coastal resources management guidelines. Coastal Publications No. 2, Renewable Resources Information Series.* Washington, DC: U.S. Department of the Interior, National Park Service and U.S. Agency for International Development.
Snedaker, S. C., and E. J. Lahmann. 1988. Mangrove understory absence: A consequence of evolution? *J. Trop. Ecol.* 4:311-314.
Snedaker, S. C., and A. E. Lugo. 1973. *The role of mangrove ecosystems in the maintenance of environmental quality and high productivity of desirable fisheries.* Final report on Contract No. 14-16-008-606 to the Bureau of Sport Fisheries and Wildlife, Atlanta, Georgia.
Snedaker, S. C., and R. L. Stanford. 1976. *Ecological studies of a subtropical terrestrial biome.* Final report to Florida Power & Light Co., Miami, Florida.
Snedaker, S. C., J. A. Jimenez, and M. S. Brown. 1981. Anomalous aerial roots in *Avicennia germinans* (L.) L. in Florida and Costa Rica. *Bull. Mar. Sci.* 3(2):467-470.
South Florida Water Management District. 1988. *Draft surface water improvement and management (SWIM) plan for Biscayne Bay.* West Palm Beach, FL.
Springer, V. G., and A. J. McErlean. 1962a. A study of the behavior of some tagged South Florida coral reef fishes. *Am. Midl. Nat.* 67:386-397.
Springer, V. G., and A. J. McErlean. 1962b. Seasonality of fishes on a South Florida shore. *Bull. Mar. Sci. Gulf Caribb.* 12:39-60.
Squires, D. 1964. Biological results of the Chatham Island 1954 expedition: Scleractinia. *New Zealand Oceanogr. Inst. Mem.* 29:1-29.
Starck, W. A. II. 1968. List of fishes of Alligator Reef, Florida, with comments on the nature of the Florida reef fauna. *Undersea Biol.* 1:1-40.
Stephens, G. 1962. Uptake of organic material by aquatic invertebrates. I. Uptake of glucose by the solitary coral *Fungia scutaria*. *Biol. Bull.* 123:648-659.
Stetson, T., D. Squires, and R. Pratt. 1962. Coral banks occurring in deep water on the Blake Plateau. *Am. Mus. Novit.* 2114:1-39.
Stewart, C. R., and A. D. Hanson. 1980. Proline accumulation as a metabolic response to water stress. In *Adaptation of plants to water and high temperature stress*, ed. N. C. Turner and P. J. Kramer. New York: John Wiley and Sons.
Stoddard, D. R. 1962. Catastrophic storm effects on the British Honduras reefs and cays. *Nature* 196:512-515.
Stoddard, D. R. 1969. Ecology and morphology of recent coral reefs. *Biol. Rev. Camb. Philos. Soc.* 44:433-498.
Stokes, F., and C. Stokes. 1980. *Handguide to the coral reef fishes of the Caribbean and adjacent tropical waters including Florida, Bermuda, and the Bahamas.* New York: Lippincott and Crowell Publ.
Stoner, A. W. 1980. The role of seagrass biomass in the organization of benthic macrofaunal assemblages. *Bull. Mar. Sci.* 30:537-551.
Stoner, A. W. 1983. Distributional ecology of amphipods and tanaidaceans associated with three seagrass species. *J. Crust. Biol.* 3:4:505-518.
Strawn, K. 1961. Factors influencing the zonation of submerged cotyledons at Cedar Key, Florida. *J. Wildl. Manage.* 25(2):178-189.
Sugg, A. L., L. Pardue, and R. L. Carrodus. 1970. Memorable Hurricanes of the United States since 1873. *NOAA Tech. Memo. NWS* SR-56, U.S. Dept. Commerce, Fort Worth, TX.
Sullivan, B., D. Faulkner, and L. Webb. 1983. Siphonodictidine: A metabolite of the burrowing sponge *Siphonodictyon* sp. that inhibits coral growth. *Science* 221:1175-1176.
Sykes, J. E., and J. H. Finucane. 1966. Occurrence in Tampa Bay, Florida of immature species dominant in Gulf of Mexico commercial fisheries. *U.S. Fish. Wildl. Serv. Fish. Bull.* 65:369-379.
Szmant-Froelich, A. 1985. The effect of colony size on the reproductive ability of the Caribbean coral *Montastraea annularis* (Ellis and Solander). In *Proceedings, Fifth International Coral Reef Congress, Tahiti*, 4:295-300. Moorea, French Polynesia: Antenne Museum-EPHE.
Tabb, D. C. 1966. The estuary as a habitat for spotted seatrout, *Cynoscion nebulosus*. *Am. Fish. Soc. Spec. Publ.* 3:59-67.
Tabb, D. C., D. L. Dubrow, and R. B. Manning. 1962. *The ecology of northern Florida Bay and adjacent estuaries.* Florida State Bd. Conserv. Tech. Ser. No. 39. St. Petersburg, FL.
Taylor, D. 1983. The black band disease in Atlantic reef corals. II. Isolation, cultivation, and growth of *Phormidium corallyticum*. *Mar. Ecol. Prog. Ser.* 4(4):321-328.
Taylor, D. L., ed. 1977. *Proceedings, Third International Coral Reef Symposium, Miami*, 2 volumes. Miami: Rosenstiel School of Marine and Atmospheric Science, Univ. of Miami.
Teas, H. J. 1974. *Mangroves of Biscayne Bay.* Metropolitan Dade County Commission. Univ. of Miami, Coral Gables, FL.
Teas, H. J., and J. Kelly. 1975. Effects of herbicides on mangroves of South Vietnam and Florida, In *Proceedings, International symposium on biology and management of mangroves, Vols. I and II*, ed. G. Walsh, S. Snedaker, and H. Teas, 719-728. Gainesville: Inst. Food Agric. Sci., Univ. of Florida.
Teichert, C. 1958. Cold and deep-water coral banks. *Am. Assoc. Pet. Geol. Bull.* 42:1064-1082.
Te Strake, D., W. C. Jaap, E. Truby, and R. Reese. 1988. Fungal filaments in *Millepora complanata* Lamarck, 1816 (Cnidaria: Hydrozoa) after mass expulsion of zooxanthellae. *Fla. Sci.* 5:185-188.
Thayer, G. W., D. R. Colby, and W. F. Hettler, Jr. 1987. Utilization of the red mangrove prop roots habitat by fishes in South Florida. *Mar. Ecol. Prog. Ser.* 35:25-38.
Thayer, G. W., K. A. Bjorndal, J. C. Ogden, S. L. Williams, and J. C. Zieman. 1984. Role of larger herbivores in seagrass communities. *Estuaries* 7(4A):351-376.
Thom, B. G. 1982. Mangrove ecology - a geomorphological perspective, . In *Mangrove ecosystems in Australia: Structure, function and management. Proceedings of the Australian National Mangrove Workshop*, ed. B. F. Clough, 3-7. Canberra: Australian National Univ. Press.
Thomas, C., and J-E. Ong 1981. Effect of heavy metal zinc and lead on *Rhizophora mucronata* Lam. and *Avicennia alba* Bl. seedlings. In *Proceedings, Asian Mangrove Symposium, 25-29 Aug. 1980*, ed. E. Soepadmo. Kuala Lumpur, Malaysia.
Thomas, L. P., D. R. Moore, and R. C. Work. 1961. Effects of Hurricane Donna on the turtle grass beds of Biscayne Bay, Florida. *Bull. Mar. Sci. Gulf Caribb.* 11:191-197.
Thorhaug, A. and M. A. Roessler. 1977. Seagrass community dynamics in a subtropical estuarine lagoon. *Aquaculture* 12:253-277.

Tomascik, T., and F. Sander. 1985. Effects of eutrophication on reef-building corals: I. Growth rate of the reef-building coral *Montastraea annularis*. *Mar. Biol.* 87:143-155.
Tomlinson, P. B. 1978. Branching and axis differentiation in tropical trees. In *Tropical trees as living systems*, ed. P. B. Tomlinson and M. H. Zimmermann, 187-207. Cambridge: Cambridge Univ. Press.
Tomlinson, P. B. 1980. Leaf morphology and anatomy in seagrasses. In *Handbook of seagrass biology: An ecosystem perspective*, ed. R. C. Phillips and C. P. McRoy, 7-28. New York: Garland STPM Press.
Tomlinson, P. B. 1986. *The botany of mangroves*. Cambridge: Cambridge Univ. Press.
Tripp, M., and R. C. Harriss. 1975. Role of mangrove vegetation in mercury cycling in the Florida Everglades. In *Environmental biogeochemistry, Vol. 2. Metals transfer and ecological mass balances*, ed. J. O. Nriagu, 489-497. Ann Arbor: Ann Arbor Sci. Publ.
Truman, R. 1961. The eradication of mangroves. *Aust. J. Sci.* 24:198-199.
Tschirley, F. H. 1969. Defoliation in Vietnam. *Science* 163:779-786.
Tunnicliffe, V. 1981. Breakage and propagation of the stony coral *Acropora cervicornis*. *Proc. Natl. Acad. Sci. U.S.A.* 78:2427-2431.
Turner, R. E. 1977. Intertidal vegetation and commercial yields of penaeid shrimp. *Trans. Am. Fish. Soc.* 106(5):411-416.
Tursch, B. 1982. Chemical protection of a reef fish *Abudefduf leucogaster* by a soft coral *Litophyton viridis*. *J. Chem. Ecol.* 8(11):1421-1428.
Twilley, R. R., A. E. Lugo, and C. Patterson-Zucca. 1986. Litter production and turnover in basin mangrove forests in Southwest Florida. *Ecology* 67(3):670-683.
Vaughan, T. W. 1911. Recent Madreporaria of southern Florida. *Carnegie Inst. Wash. Year Book* 8:135-144.
Vaughan, T. W. 1915. The geological significance of the growth-rate of the Floridian and Bahamian shoal-water corals. *J. Wash. Acad. Sci.* 5:591-600.
Vaughan, T. W. 1918. The temperature of the Florida coral reef tract. *Carnegie Inst. Wash. Publ.* 213:321-339.
Vaughan, T. W., and J. W. Wells. 1943. Revision of the suborders, families, and genera of the Scleractinia. *Geol. Soc. Am. Spec. Pap.* 44:1-363.
Vazquez, M. A. 1983. The effects of impounding on a mangrove forest. M.S. thesis, Univ. of Florida.
Verhoeven, J. T. A. 1975. *Ruppia*-communities in the Camargue, France. Distribution and structure in relation to salinity and salinity fluctuations. *Aquat. Bot.* 1:217-241.
Vicente, V. 1978. An ecological evaluation of the west Indian demosponge *Anthosigmella varians* (Hadromerida Spirastellidae). *Bull. Mar. Sci.* 28(4):771-779.
Vicente, V. P., J. A. Arroyo-Agiuhi, and J. A. Rivera. 1980. *Thalassia* as a food source: Importance and potential in the marine and terrestrial environment. *J. Agric. Univ. Puerto Rico* 64:107-120.
Virnstein, R. W. 1987. Seagrass-associated invertebrate communities of the southeastern United States. In *Proceedings of the symposium on subtropical-tropical seagrasses of the southeastern United States*, ed. M. Durako, R. Phillips, and R. Lewis, 89-116. Florida Mar. Res. Publ. No. 42. St. Petersburg, FL.
Virnstein, R. W, P. S. Mikkelsen, K. D. Cairns, and M. A. Capone. 1983. Seagrass beds vs. sand bottoms: the trophic importance of their associated benthic invertebrates. *Fla. Sci.* 46:363-381.
Voss, G. L. 1973. Sickness and death in Florida's coral reefs. *Nat. Hist.* 82:40-47.
Voss, G. L. 1976. *Seashore Life of Florida and the Caribbean*. Miami: E.A. Seemann Publ. Co. Inc.
Voss, G. L. 1983. *An environmental assessment of the Key Largo National Marine Sanctuary*. Report prepared for the Marine Sanctuary Program Office, National Oceanic and Atmospheric Administration, Washington, DC.
Voss, G. L. 1988. *Coral reefs of Florida*. Sarasota: Pineapple Press.
Walker, N. D. 1981. January water temperatures kill Florida fauna. *Coast. Oceanogr. Climatol. News* 3:30.
Walsh, G. E. 1974. Mangroves: A review. In *The ecology of halophytes*, ed. R. J. Reimold and W. H. Queen. New York: Academic Press.
Walsh, G. E., and T. E. Grow. 1972. Composition of *Thalassia testudinum* and *Ruppia maritima*. *Q. J. Fla. Acad. Sci.* 35:97-108.
Walsh, G. E., K. A. Ainsworth, and R. Rigby. 1979. Resistance of red mangrove (*Rhizophora mangle* L.) seedlings to lead, cadmium, and mercury. *Biotropica* 11(1):22-27.
Walsh, G. E., R. Barrett, G. H. Cook, and T. A. Hollister. 1973. Effects of herbicides on seedlings of the red mangrove, *Rhizophora mangle* L. *BioScience* 23:361-364.
Walsh, G. E., T. A. Hollister, and J. Forester. 1974. Translocation of four organochlorine compounds by red mangrove (*Rhizophora mangle* L.) seedlings. *Bull. Environ. Contam. Toxicol.* 12(2):129-135.
Walton, R., W. M. Williams, M. P. Wang, and L. A. Roesner. 1985. Coral reef modeling: Key Largo case study. *Proc. Coast. Zone* 85:2420-2438.
Warme, J.E. 1975. Borings as trace fossils, and the processes of marine bioerosion. In *The Study of Trace Fossils*, ed. R.W. Frey, 181-227. New York: Springer-Verlag.
Watson, J. G. 1928. *Mangrove forests of the Malay Peninsula*. Malayan Forest. Rec. No. 6. Singapore: Fraser and Neave, Ltd.
Webb, K. L., W. D. Du Paul, W. Wiebe, W. Sottile, and R. E. Johannes. 1975. Enewetak (Eniwetok) Atoll: Aspects of the nitrogen cycle on a coral reef. *Limnol. Oceanogr.* 20:198-210.
Weinstein, M. P., and K. L. Heck. 1979. Ichthyofauna of seagrass meadows along the Caribbean coast of Panama and in the Gulf of Mexico: composition, structure and community ecology. *Mar. Biol.* 50:97-107.
Wellington, G. M. 1980. Reversal of digestive interactions between Pacific reef corals - mediation by sweeper tentacles. *Oecologia* 47:340-343.
Wellington, G. M. 1982. An experimental analysis of the effects of light and zooplankton on coral zonation. *Oecologia* 52:311-320.
Wells, J. W. 1956. Scleractinia. In *Treatise on invertebrate paleontology* ed. R. C. Moore, F328-F334. Manhattan: Geological Society of America and Univ. Kansas Press.
Wells, J. W. 1957. Coral reefs. In *Treatise on marine ecology and paleoecology, Vol. 1, Ecology*, ed. J.W. Hedgepeth, 609-631. Geol. Soc. Am. Mem. No. 67.
Wells, S. M. 1988. *Coral reefs of the world. Vol. 1, Atlantic and eastern Pacific; Vol. 2, Indian Ocean and Red Sea; Vol. 3, Central and western Pacific*. Cambridge: United Nations Environment Program and International Union for the Conservation of Nature.
Westlake, D. F. 1963. Comparisons of plant productivity. *Biol. Rev.* 38:385-425.
Wethey, D., and J. Porter. 1976. Sun and shade differences in productivity of reef corals. *Nature* 262:281-282.
Whale, C. M. 1980. Detection, pursuit and overgrowth of tropical gorgonians by milleporid hydrocorals, Perseus and Medusa revisited. *Science* 209:689-691.

Wheaton, J. L., and W. C. Jaap. 1988. Corals and other prominent benthic Cnidaria of Looe Key National Marine Sanctuary, Florida. *Fla. Mar. Res. Publ.* 43:1-25.
Whittaker, R. H., G. E. Likens, and H. Lieth. 1975. Scope and purpose of this volume. In *Primary productivity of the biosphere*, ed. H. Lieth and R. H. Whittaker, 3-5. New York: Springer-Verlag.
Wiginton, J. R., and C. McMillan. 1979. Chlorophyll composition under controlled light conditions as related to the distribution of seagrasses in Texas and the U.S. Virgin Islands. *Aquat. Bot.* 6:171-184.
Williams, S. L., and C. P. McRoy. 1982. Seagrass productivity: The effect of light on carbon uptake. *Aquat. Bot.* 12:321-344.
Wilson, J. 1979. "Patch" development of the deep-water coral *Lophelia pertusa* (L) on Rockall Bank. *J. Mar. Biol. Assoc. U. K.* 59:165-177.
Windhorn, S., and W. Langley. 1974. *Yesterday's Florida Keys*. Miami: E.A. Seemann Publ. Co.
Wood, E. J. F., W. E. Odum, and J. C. Zieman. 1969. Influence of seagrasses on the productivity of coastal lagoons. In *Lagunas Costeras: Un Simposio Mem. Simp. Intern*, 495-502. Mexico: UNAM-UNESCO.
Woodley, J., et al. 1981. Hurricane Allen's impact on Jamaican coral reefs. *Science* 214:749-755.
Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1985. *Southwest Florida shelf ecosystems study - Year 2*. New Orleans: U.S. Department of the Interior, Minerals Management Service.
Wulff, J. 1984. Sponge-mediated coral reef growth and rejuvenation. *Coral Reefs* 3(3):157-163.
Wulff, J., and L. Buss. 1979. Do sponges hold coral reefs together? *Nature* 281:474-475.
Yokel, B. J. 1975a. *Rookery Bay land use studies: environmental planning strategies for the development of a mangrove shoreline*. Estuarine Biol. 5. Washington DC: Conservation Foundation.
Yokel, B. J. 1975b. *A comparison of animal abundance and distribution in similar habitats in Rookery Bay, Marco Island and Fakahatchee on the southwest coast of Florida*. Preliminary report from Rosenstiel School of Marine and Atmospheric Science to the Deltona Corp., Miami, FL.
Yonge, C. M. 1930. Studies on the physiology of corals. I. Feeding mechanisms and food. *Sci. Rep. Great Barrier Reef Exped.* 1:13-57.
Yonge, C. M. 1963. The biology of coral reefs. In *Advances in Marine Biology*, ed. F. Russell, 1:209-260. New York: Academic Press.
Zeiller, W. 1974. *Tropical marine invertebrates of southern Florida and the Bahamas Islands*. New York: John Wiley and Sons.
Zieman, J. C. 1972. Origin of circular beds of *Thalassia* (Spermatophyta: Hydrocharitacea) in south Biscayne Bay, Florida, and their relationship to mangrove hammocks. *Bull. Mar. Sci.* 22:559-574.
Zieman, J. C. 1975a. Quantitative and dynamic aspects of the ecology of turtle grass, *Thalassia testudinum*. In *Estuarine Research, Vol. 1.*, ed. L. E. Cronin, 541-562. New York: Academic Press.
Zieman, J. C. 1975b. Seasonal variation of turtle grass, *Thalassia testudinum* (Konig), with reference to temperature and salinity effects. *Aquat. Bot.* 1:107-123.
Zieman, J. C. 1975c. Tropical seagrass ecosystems and pollution. In *Tropical marine pollution*, ed. E. J. F. Wood and R. E. Johannes, Chapter 4. New York: Elsevier Publ. Co.
Zieman, J. C. 1976. The ecological effects of physical damage from motorboats on turtle grass beds in southern Florida. *Aquat. Bot.* 2:127-139.
Zieman, J. C. 1982. *The ecology of seagrasses of South Florida: A community profile*. FWS/OBS-82/25. Washington, DC: U.S. Fish and Wildlife Service, Biological Services Program.
Zieman, J. C. 1987. A review of certain aspects of the life, death, and distribution of seagrasses of the southeastern United States 1960-1985. In *Proceedings of the symposium on subtropical-tropical seagrasses of the southeastern United States*, ed. M. Durako, R. Phillips, and R. Lewis, 53-76. Florida Mar. Res. Publ. No. 42. St. Petersburg, FL.
Zieman, J. C., and R. G. Wetzel. 1980. Methods and rates of productivity in seagrasses. In *Handbook of Seagrass Biology*, ed. R. C. Phillips and C. P. McRoy, 87-116. New York: Garland STPM Press.
Zieman, J. C., and E. J. F. Wood. 1975. Effects of thermal pollution on tropical-type estuaries, with emphasis on Biscayne Bay, Florida. In *Tropical marine pollution*, ed. E. J. Ferguson Wood and R. E. Johannes, Chapter 5. New York: Elsevier Publ. Co.
Zieman, J. C., and R. T. Zieman. 1989. *The ecology of the seagrass meadows of the west coast of Florida: A community profile*. U.S. Fish Wildl. Serv. Biol. Rep. 85(7.25). Washington, DC.
Zieman, J. C., J. W. Fourqurean, and R. L. Iverson. 1989. Distribution, abundance, and productivity of seagrasses and macroalgae in Florida Bay. *Bull. Mar. Sci.* 44:292-311.
Zieman, J. C., R. L. Iverson, and J. C. Ogden. 1984a. Herbivory effects on *Thalassia testudinum* leaf growth and nitrogen content. *Mar. Ecol. Prog. Ser.* 15:151-158.
Zieman, J. C., R. Orth, R. C. Phillips, G. Thayer, and A. Thorhaug. 1984b. The effects of oil on seagrass ecosystems. In *Recovery and restoration of marine ecosystems*, ed. J. Cairns and A. Buikema, Ch. 2. Ann Arbor: Ann Arbor Press.
Zieman, J. C., G. W. Thayer, M. B. Robblee, and R. T. Zieman. 1979. Production and export of seagrasses from a tropical bay. In *Ecological processes in coastal and marine systems*, ed. R. J. Livingston, 21-34. New York: Plenum Press.
Zieman, J. C., J. Fourqurean, M. Robblee, M. Durako, P. Carlson, D. Porter, R. Zieman, L. Muhelstein, and G. Powell. 1988. A catastrophic die-off of seagrasses in Florida bay and Everglades National Park: Extent, effects, and potential causes. *Eos Trans. Am. Geophys. Union* 69:1111.
Zimmerman, M. S., and R. J. Livingston. 1976. Seasonality and physico-chemical ranges of benthic macrophytes from a North Florida estuary (Apalachee Bay). *Contrib. Mar. Sci.* 20:34-45.
Zlatarski, V., and N. Estalella. 1982. *Les Scleractiniaires de Cuba Avec des Donnees sur les Organismes Associes*. Sofia, Bulgaria: del Academie Bulgare des Sciences.

CHAPTER 5
OFFSHORE BENTHIC COMMUNITIES

Neal W. Phillips and M. John Thompson

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INTRODUCTION

Offshore benthic communities of the continental shelf (water depths of 10 to 200 m) have not been studied as well as South Florida's coastal and nearshore communities, such as mangrove forests, coral reefs, and seagrass beds. From the perspective of this study, the offshore communities are important because they might be more directly affected by drilling activities in Federal waters.

A community is an association of interacting populations, usually defined by the nature of their interaction or the place in which they live (Ricklefs 1979). In coral reefs, mangrove forests, and *Thalassia* seagrass beds, a few species provide the habitat structure and are the focus of community interactions. Offshore benthic communities are not so neatly defined; most often, communities are recognized according to habitat type (e.g., soft bottom, hard bottom) and sampling methods (e.g., macroinfauna by box coring, fishes by trawling) rather than by the presence of a dominant species.

Among U.S. continental shelf environments studied in recent years, the Southwest Florida shelf is unusual in several respects. The sediments and the underlying rock are almost entirely carbonate, reflecting the fact that the West Florida shelf has been cut off from the terrigenous sediment load of the Mississippi River since Jurassic time (roughly 150 million years ago) (Ginsburg and James 1974). The sand veneer over bedrock is thin, particularly near shore (where many patch reefs are seen) and over ancient,

partially buried reef features on the middle shelf (Pulley Ridge) and outer shelf (Howell Hook). The climate is favorable for tropical species, with near-bottom temperatures at or above 18 ° C most of the time (although occasional winter cold fronts have been known to kill reef fishes and invertebrates in shallow water). The availability of hard substrate, the favorable climate, and the proximity to sources of colonizing reef biota help to explain the presence of a diverse sessile epifauna, including many species of corals and sponges commonly found on reefs in the Florida Keys and the Caribbean.

Areas of dense sessile epifauna on the continental shelf are often referred to as live bottom. The term was coined by fishery scientists to describe such areas on the continental shelf of the South Atlantic Bight (Cummins et al. 1962; Struhsaker 1969). In general, live bottom areas are considered valuable because they attract commercially and ecologically important species of fish (Darcy and Gutherz 1984). The Minerals Management Service (MMS) considers live bottom areas to be valuable and sensitive to oil- and gas-related activities, and accords them special protection under lease stipulations (MMS 1987).[1] This topic is discussed at the end of the chapter.

DATA SOURCES

This chapter focuses mainly on the offshore benthic communities of the Southwest Florida shelf north of the Florida Keys and the Dry Tortugas, where field studies have recently been completed by the MMS. Less information is available *in usable form* for the shelf between the Florida Reef Tract and the Straits of Florida. Although many trawl samples have been collected from this area, particularly by University of Miami researchers aboard the R/V *Gerda*, the samples have been analyzed by individual taxonomists (usually students for dissertation or thesis projects), and no synthesis or ecological overview is available.

Nearly all of the information available for offshore benthic communities in the study area is descriptive; little information is available about ecological relationships. As noted by Rabalais and Boesch (1987), many aspects of the biology of continental shelf benthos are not as well understood as those of littoral zone and the deep sea.

Early Studies

The first benthic sampling in the study area occurred in 1867 and 1868, when Count L. F. Pourtales dredged between the Florida Keys and Cuba during cruises of the U.S. Coast Guard survey ships *Bibb* and *Corwin* (Galtsoff 1954; Staiger 1970). The samples yielded many new species of corals and echinoderms. Subsequently, dredge samples were collected in the Straits of Florida and on the West Florida shelf during cruises of the steamers *Blake* (1877-1880), *Albatross* (1884-1890), and *Fish Hawk* (1901-1902) (Agassiz 1888; Galtsoff 1954). Researchers from Harvard University and the University of Havana trawled in the Straits in 1938 and 1939 aboard the R/V *Atlantis* out of Woods Hole (Staiger 1970). Beginning in 1950, the Bureau of Commercial Fisheries conducted an exploratory fishing program that included about 100 stations in the Straits of Florida; however, the material was distributed to various taxonomists, and no ecological overview of the results is available (Staiger 1970).

Early studies provided a preliminary indication that the shelf in the study area harbors many types of reef epibiota. It was not until more recently that systematic sampling efforts confirmed and elaborated on those findings.

[1]The MMS defines live bottom as "seagrass communities; or those areas which contain biological assemblages consisting of such sessile invertebrates as sea fans, sea whips, hydroids, anemones, ascidians, sponges, bryozoans, or corals living upon and attached to naturally occurring hard or rocky formations with rough, broken, or smooth topography; or areas whose lithotope favors the accumulation of turtles, fishes, and other fauna" (MMS 1987).

Recent Studies

Hourglass Cruises

The first intensive sampling of offshore benthos on the West Florida shelf began in 1966 with the Hourglass Cruises, which covered the region north of the study area between Tampa Bay and Sanibel Island (Joyce and Williams 1969). Monthly dredge and trawl samples were collected between 1965 and 1967 as part of this study, and the results for various taxonomic groups continue to appear from time to time in a series of papers published by the Florida Department of Natural Resources, Marine Research Laboratory. Lyons (1979) devised a zonation scheme for West Florida shelf fauna on the basis of Hourglass mollusc collections.

MAFLA Study

From 1974 to 1978, the Bureau of Land Management (BLM) funded the Mississippi-Alabama-Florida (MAFLA) studies, which included trawl and box core sampling off Charlotte Harbor and Naples (Dames & Moore 1979). The data from this study were compiled in a final report, including chapters on macroepifauna (Hopkins 1979), as well as macroinfaunal crustaceans (Heard 1979), molluscs (Blake 1979), and polychaetes (Vittor 1979). None of the MAFLA stations are in the study area.

Southwest Florida Shelf Ecosystems Study

Between 1980 and 1987, the U.S. Department of the Interior funded a series of environmental investigations known collectively as the Southwest Florida Shelf Ecosystems (SOFLA) Study. The study area extended from Charlotte Harbor to the Dry Tortugas, and from water depths of 10 to 200 m (**Figure 5.1**). Field sampling began in October 1980 and continued through December 1985. A literature search-and-synthesis project followed in 1986 and 1987 (Environmental Science and Engineering, Inc. et al. 1987).

There were two main elements to the study: habitat mapping and benthic station sampling. Sampling methods are detailed by Woodward-Clyde Consultants and Continental Shelf Associates, Inc. (1985), Danek and Lewbel (1986), and Continental Shelf Associates, Inc. (1987a). Water column sampling was also conducted but is not discussed here (see Woodward-Clyde Consultants and Skidaway Institute of Oceanography 1983).

To characterize substratum types and benthic communities on a broad scale, 14 transects (**Figure 5.1**) were surveyed geophysically (side-scan sonar, subbottom profiler) and visually (underwater video and still cameras). Two atlases were prepared to illustrate the results (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1983; Continental Shelf Associates, Inc. 1985). One cross-shelf transect (E), two short transects near the Dry Tortugas (M and N), and portions of three other transects (D, G, and K) are located in the current study area (**Figure 5.1**).

Fifty-five stations were sampled two, four, or more times during the study (**Figure 5.1**). Water depths ranged from 10 to 160 m. Twenty-six stations were located in areas of dense sessile epifauna and are referred to as live bottom stations; these were sampled remotely by dredge, trawl, and underwater video and still cameras. Some live bottom stations were sampled more intensively with *in situ* arrays during 1984 and 1985 (Danek and Lewbel 1986). Twenty-nine stations located in areas of sparse sessile epifauna were sampled for macroinfauna and sediments. Trawl samples were also collected at some of these stations.

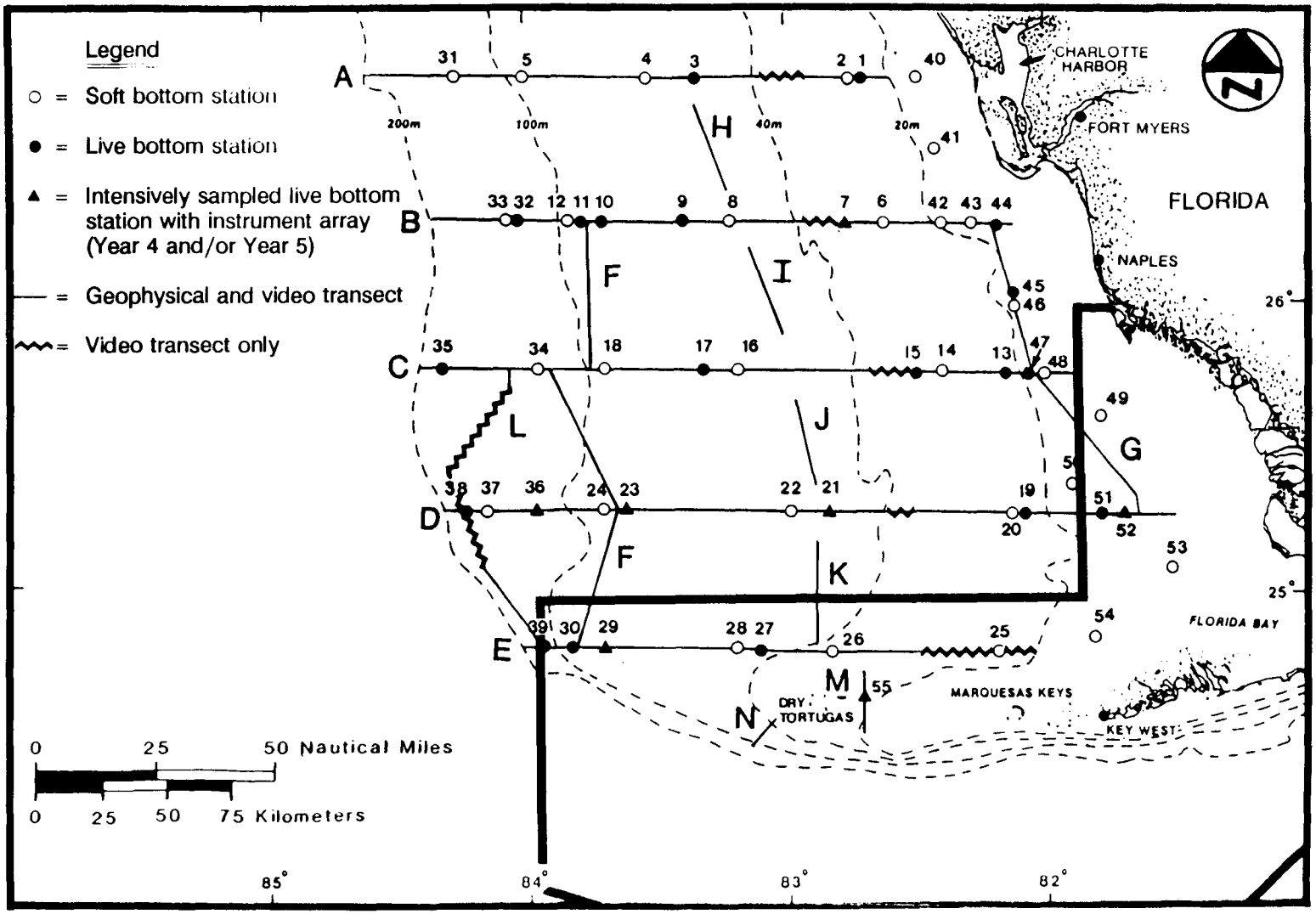

Figure 5.1. Stations (1 to 55) and transects (A to N) sampled during the Southwest Florida Shelf Ecosystems Study (From: Environmental Science and Engineering, Inc. et al. 1987). The heavy, solid line is the study area boundary for this synthesis.

Southwest Florida Shelf Nearshore Benthic Habitat Study

A more recent MMS study (1987-1989) used a combination of aerial and shipboard surveys to map habitat distributions from shore out to a depth of 40 m. The aerial overflights covered much of the inner Southwest Florida shelf, as well as Florida Bay, parts of the Florida Keys, and the Dry Tortugas. A number of stations were sampled photographically by divers, and transects were surveyed by towed divers or underwater television (**Figure 5.2**). The main goal of the study was to map benthic habitats in areas that had not been surveyed during the previous MMS study. The study also focused on the distribution, seasonality, density, and depth limits of the seagrass *Halophila decipiens* (Continental Shelf Associates, Inc. 1989).

Other Relevant Studies

Since 1962, extensive dredge and trawl sampling has been conducted in the Straits of Florida by University of Miami researchers during cruises of the R/V *Gerda*. Although several theses and dissertations have resulted from these collections (e.g., Robins 1968; Devany 1969; Staiger 1970), no overview of benthic communities has been prepared (G. Voss, pers. comm. 1988, Univ. of Miami). More than 1,200 stations have been sampled, with about 60% in waters shallower than 200 m (Staiger 1970).

Information on benthic habitats offshore the Florida Reef Tract is available from several studies. Submersible surveys conducted off Key Largo in 1973 by Harbor Branch Foundation investigators documented the presence of a deep reef seaward of Molasses Reef (Antonius 1974). Later, the submersible was used to survey deepwater habitats offshore of French Reef, The Elbow, and Carysfort Reef (in the Key Largo National Marine Sanctuary) in conjunction with a side-scan sonar and bathymetric survey (Jameson 1981). Results of submersible surveys of deepwater habitats off Looe Key are summarized by the National Oceanic and Atmospheric Administration (NOAA) (1980).

Parker et al. (1983) surveyed large areas of the South Atlantic and West Florida shelf with underwater television to estimate the proportion of reef habitat. Darcy and Gutherz (1984) summarized the results of trawl investigations north of the study area; although the study was mainly concerned with fishes, some information was presented on the occurrence of "sponge bottom." Intensive studies of pink shrimp populations have been conducted in and near the Tortugas shrimp grounds and the Tortugas Sanctuary (Costello and Allen 1966; Klima and Costello 1982).

DISTRIBUTION OF BENTHIC HABITATS

Two general types of offshore benthic habitats occur in the study area: hard bottom and soft bottom. Over much of the Southwest Florida shelf, these habitats are interspersed in a complex, patchy mosaic.

Offshore hard bottom habitats in the study area usually consist of rock covered by a thin, mobile sand veneer; outcrops are rarely seen and are usually <1 m in relief. Coralline algal nodules, algal pavements, and shell rubble provide additional hard substrate in certain areas. Where hard substrate is present, it is usually colonized by a diverse epibiota, including macroalgae, stony corals, octocorals, sponges, hydroids, ascidians, bivalves, bryozoans, and others. The assemblage is a mix of tropical and warm temperate species. Because of the mobile sand veneer, many of these species are apparently tolerant to sedimentation and scour.

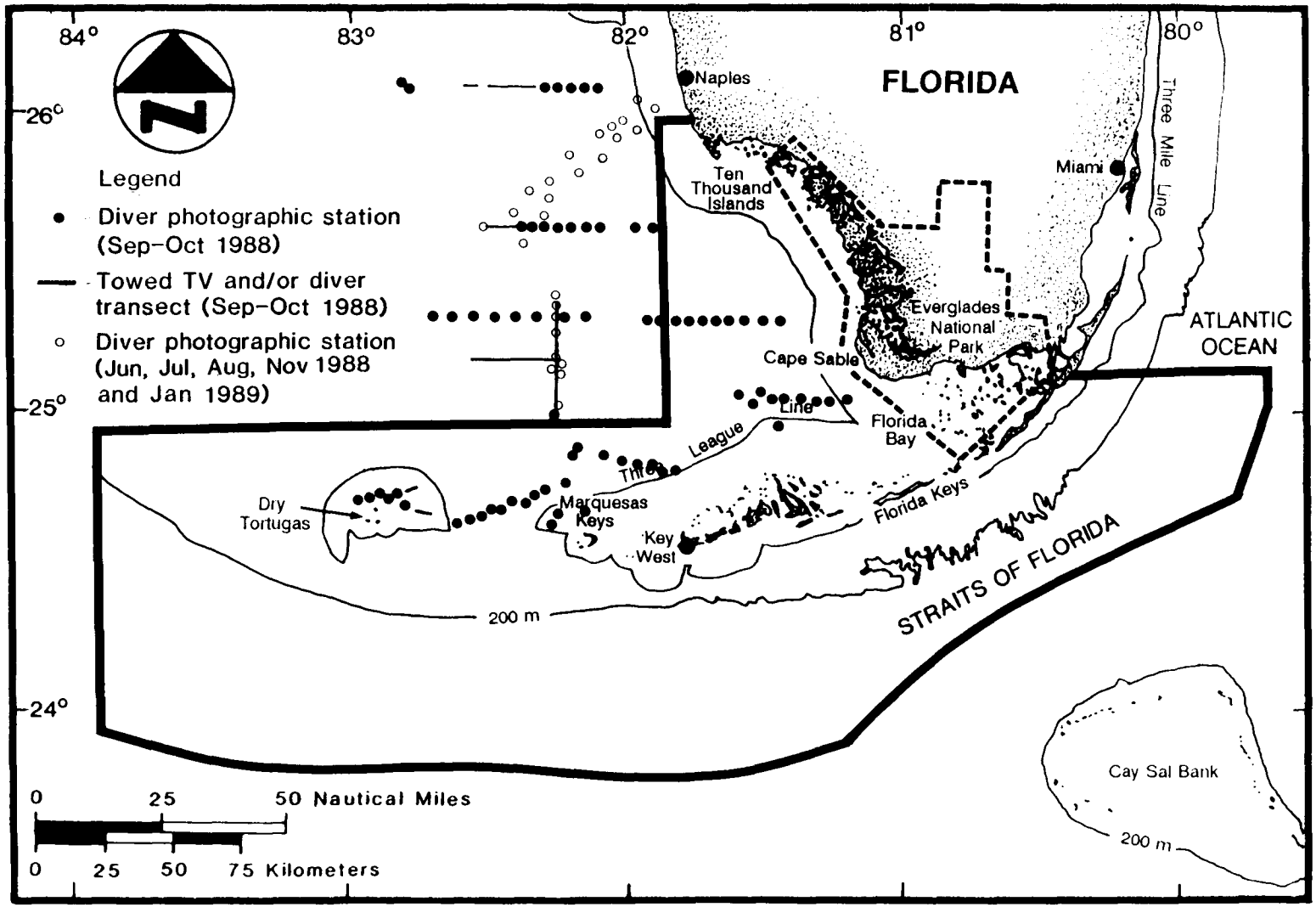

Figure 5.2. Stations and transects sampled during the Southwest Florida Nearshore Benthic Habitat Study (Adapted from: Continental Shelf Associates, Inc. 1989). The heavy, solid line is the study area boundary for this synthesis.

Soft bottom habitats in the study area consist largely of carbonate sand. Two exceptions are near the mainland coast, where quartz sand occurs, and northeast of the Dry Tortugas and Marquesas Keys, where sediments are predominantly carbonate silt. Soft bottom habitats support macroinfaunal and macroepifaunal communities. On the inner shelf, many soft bottom areas are colonized by the seagrass *Halophila decipiens*. There is not enough ecological information to determine whether the *Halophila* seagrass areas constitute a distinct benthic community. This seagrass does not structure the habitat in the way that nearshore *Thalassia* beds do, and its biomass is much less than that of the nearshore species (Continental Shelf Associates, Inc. 1989).

Geologic Setting

The distribution of benthic habitats on the Southwest Florida shelf is heavily influenced by two environmental factors: geomorphology and light. Geomorphology controls sediment thickness, which determines the availability of hard substrate for attachment of sessile epifauna. The quantity and quality of light reaching the bottom controls the distribution of photosynthetic species (e.g., seagrasses and macroalgae), as well as those species containing zooxanthellae (e.g., many stony corals and octocorals). The importance of light is discussed later in this chapter.

The geology of the Southwest Florida continental margin has been reviewed in **Chapter 2**. The shelf consists of a broad, gently sloping platform that is covered by a veneer of carbonate sand. The thickness of this sand veneer varies regionally and locally, producing a complex mosaic of hard bottom and soft bottom habitats.

A major, partly buried reef complex (Pulley Ridge) occurs on the middle shelf, in a water depth of about 70 to 90 m. This feature is an important regional influence on benthic communities because it impounds sediments of the inner and middle shelf (Holmes 1981, 1985). As a result, the sand veneer generally thickens with increasing depth and distance from shore, out to the 60- or 70-m isobath (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1985). Accordingly, hard bottom habitats tend to be more common in shallow water (10 to 20 m) and over Pulley Ridge (70 to 90 m) than in intermediate water depths (Phillips et al. 1990a). The bathymetry in the 70- to 90-m depth range is irregular, and numerous ledges, holes, and depressions are seen on the seafloor (Continental Shelf Associates, Inc. 1988a). Although the reef complex is no longer active, Pulley Ridge is capped by coralline algal growths (algal nodules and algal pavements), which provide additional hard substrate for sessile epifauna even where the underlying rock is not exposed.

Sediment thickness also varies on a local scale. Direct measurements at five hard bottom stations in water depths <20 m showed that the thickness of the sand veneer varied from 0 to 18 cm within a radius of about 20 m (Continental Shelf Associates, Inc. 1987a). This variability is significant because most sponges and corals in live bottom areas are attached to hard substrate covered by 5 cm or less of sand (Marine Resources Research Institute 1984). Local variations in sediment thickness due to irregularities in the underlying rock surface could be responsible for much of the patchiness that is evident in benthic communities on the Southwest Florida shelf.

Substratum Types

Figure 5.3 shows a schematic illustration of major substratum types in the study area (Continental Shelf Associates, Inc. 1987a). Five major types are recognized:

(1) Rock outcrops (hard bottom).
(2) Thin sand over hard substrate (suspected hard bottom).
(3) Sand bottom (soft bottom).
(4) Coralline algal nodule layer over sand.
(5) Algal pavement with platelike reef corals (*Agaricia*).

Sand bottom and thin sand over hard bottom are the most common substrate types on the Southwest Florida shelf. The distinction between (thick) sand bottom and thin sand over hard bottom is a practical one based on biological evidence (presence of a dense sessile epifauna) rather than direct measurements or geophysical data, in most cases. Geophysical instruments can measure the thickness of the sand veneer, but not with sufficient resolution to be biologically meaningful.

Exposed rock is generally rare, widely scattered, and of low relief (<1 m). Patch reefs have been reported in water depths of 10 to 30 m along the Southwest Florida coast as far north as Tampa (Smith 1976). These typically are undercut ledge systems oriented parallel to isobaths, and they probably represent shoreline features preserved during a gradual rise in sea level (Smith 1976). Ledges and holes with exposed rock are seen occasionally in the 70- to 90-m depth range along Pulley Ridge. Outcrops of greater relief (up to 3 m) have been observed in some areas of the outer shelf outside of the study area (Continental Shelf Associates, Inc. 1987a). These "pinnacles" are associated with an ancient reef feature, Howell Hook (Jordan and Stewart 1959; Holmes 1981).

Coralline algal nodules are another type of substratum found on the shelf. The main concentration of these nodules is along Pulley Ridge, as described below. However, over much of the inner shelf, accumulations of nodules and coralline algal rubble are seen in the troughs of sand waves. This rubble is often colonized by hydroids, bryozoans, small sponges and octocorals, and other sessile epifauna.

Coralline algal nodules are commonly seen on and around Pulley Ridge, in the 60- to 100-m depth range. The nodules, which range in size from a few millimeters to several centimeters in diameter, provide a substratum for attachment of epiflora and sessile epifauna. Two genera of coralline algae, *Lithothamnium* and *Lithophyllum*, are believed to be the main constituents of the nodules (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1985). In general, the nodules increase in abundance toward the south on the Southwest Florida shelf; in the current study area, fused coralline algal pavements have been noted on portions of transect E (northwest of the Dry Tortugas) and transect N (southwest of the Dry Tortugas). Platelike reef corals (*Agaricia* spp.) provide additional hard substrate at these locations.

Benthic Habitats

Southwest Florida Shelf

Overall, about 30% of the Southwest Florida shelf consists of live bottom areas (Phillips et al. 1990b). This figure is similar to the value of 38% reported by Parker et al. (1983) for the 18- to 91-m depth range of the West Florida shelf as a whole. Both figures are estimates from limited visual observations. Extensive trawl collections reported by Darcy and Gutherz (1984) also indicate that live bottom is common on the West Florida shelf. **Figure 5.4** is a schematic illustration of the distribution of benthic habitats and community types on the Southwest Florida shelf, including portions of the study area.

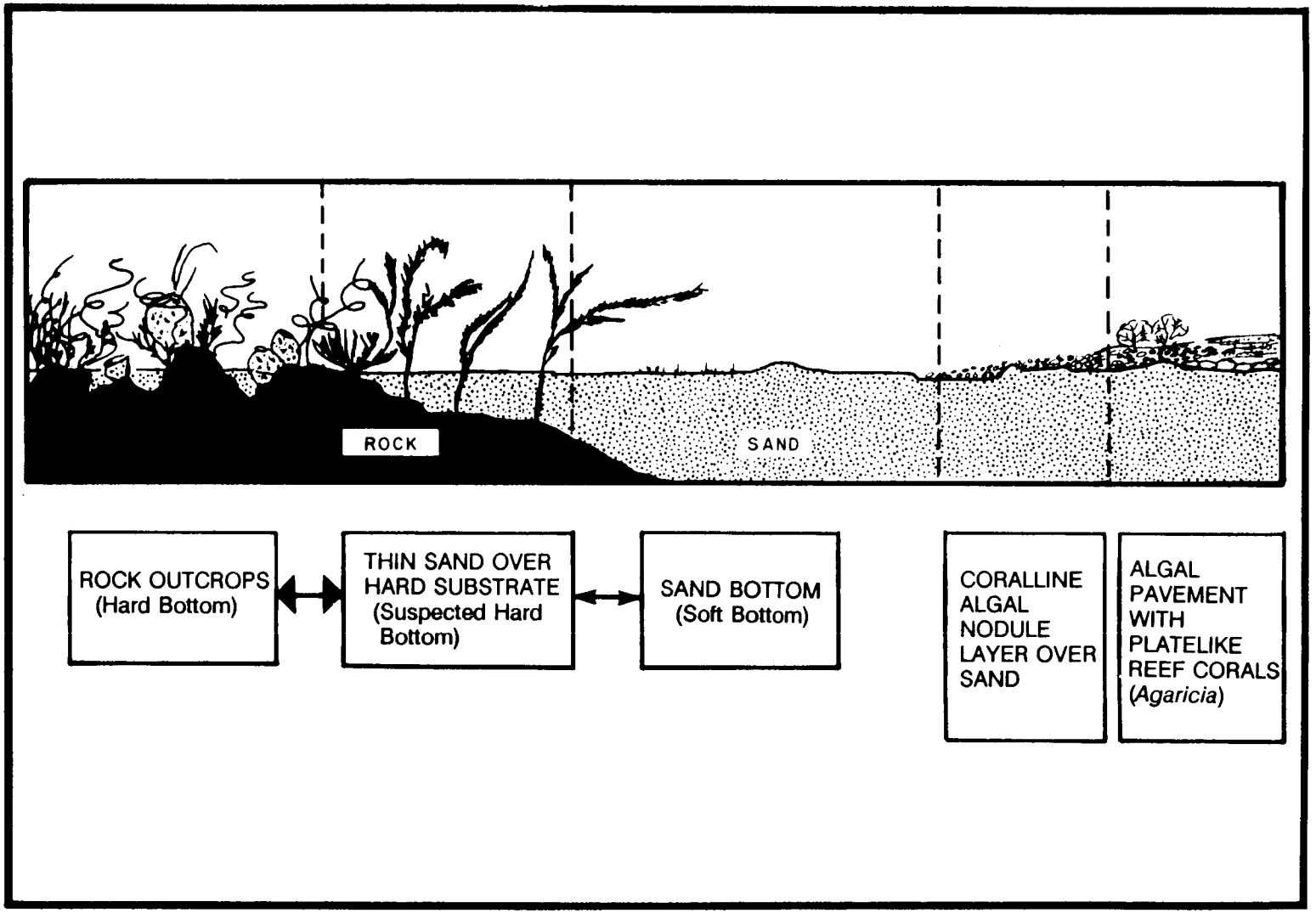

Figure 5.3. Schematic illustration of substrate types on the Southwest Florida shelf (From: Continental Shelf Associates, Inc. 1987a).

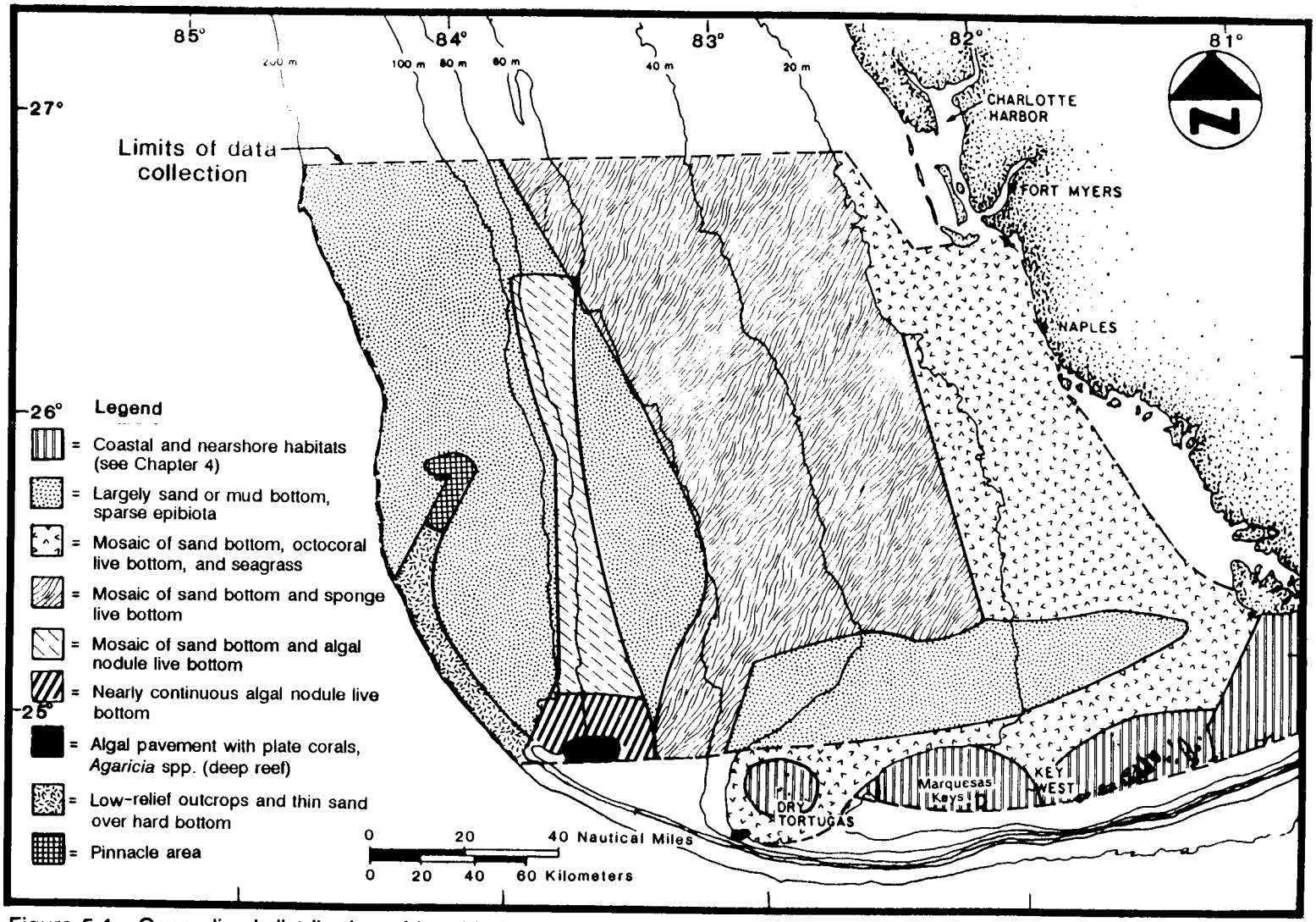

Figure 5.4. Generalized distribution of benthic habitats on the Southwest Florida shelf (Adapted from: Continental Shelf Associates, Inc. 1989; Phillips et al. 1990b).

Most of the inner shelf between Cape Romano and Cape Sable consists of a complex mosaic of thinly covered hard bottom and soft bottom (**Figure 5.4**). About 40% of the seafloor in the 10- to 20-m depth range is thinly covered hard bottom colonized by dense, sessile epifauna (Phillips et al. 1990b). Lush gorgonian growth is especially typical of these inner shelf, hard bottom areas. Soft bottom areas of the inner shelf are colonized in summer by the seagrass *Halophila decipiens* and macroalgae (*Caulerpa*, *Halimeda*, *Penicillus*, *Udotea*, etc.). Between May and September, one is likely to encounter either a dense, sessile epifaunal community or seagrass/macroalgae-covered bottom at almost any location on the inner shelf.

South of Cape Sable, the mosaic of hard bottom and soft bottom habitats is interrupted by a large area of carbonate silt which extends west of Florida Bay and north of the Dry Tortugas. Little or no hard bottom is present in this area, which includes portions of the Tortugas shrimp grounds. *Halophila decipiens* occurs only sporadically in this area.

The mosaic of hard bottom and soft bottom habitats continues along the northern coast of the Lower Keys and Marquesas, and around the Dry Tortugas (**Figure 5.4**). Because of the relatively clear water away from the mainland, the gorgonian-dominated hard bottom communities extend into deeper water (at least 27 m) near the Dry Tortugas.

The cross-shelf distribution of benthic habitats in the study area is further illustrated by **Figure 5.5**, which is based mainly on data from transect E of the SOFLA study. This transect ran east-west at 24°48'N (**Figure 5.1**). As noted above, the inner shelf off Florida Bay is predominantly carbonate silt, with a sparse epibiota. From about 50 to 65 m depth, patches of dense, sessile epifauna occur. The lush octocoral growths occurring in shallower water are no longer present; sponges and macroalgae are the most conspicuous epibiota, and small hard corals are also present.

Seaward of the 65-m isobath, extensive growths of coralline algal nodules are seen, extending for many kilometers over an area of nearly flat bottom (**Figure 5.5**). The nodule areas are dense in the study area, but sparse and patchy north of 25°N (**Figure 5.4**). Associated with the nodules are the leafy green alga *Anadyomene menziesii* and species of calcified algae (the red algae *Peyssonnelia rubra* and *P. simulans*, as well as the green alga *Halimeda*). Sparse populations of sessile epifauna such as sponges, octocoral sea whips, hard corals, and crinoids are also present in these nodule areas.

A fused, coralline algal pavement occurs in the 65- to 80-m depth range northwest of the Dry Tortugas (**Figures 5.4 and 5.5**). This area supports a deep reef community that includes platelike reef corals (*Agaricia* spp.), dense growths of the green alga *Anadyomene menziesii*, and a variety of tropical reef fishes (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1985). A similar habitat has been found in the 50- to 60-m depth range southwest of the Dry Tortugas (Danek and Lewbel 1986). More information on the deep reef community is presented later in this chapter.

Most of the outer Southwest Florida shelf is covered by a thick sand veneer. However, in the study area, the outer shelf is narrow and steep, and exposed, low-relief hard bottom occurs frequently (**Figures 5.4 and 5.5**). North of the study area, most outer shelf outcrops are concentrated along two partially buried, north-trending reef features described by Holmes (1981). The inner reef (Howell Hook) occurs in a water depth of about 150 m and is visible in the form of isolated, steep-walled "pinnacles" protruding up to 3 m above the surrounding thick sand. The outer reef occurs at the shelf break; low-relief outcrops are seen between depths of 190 and 200 m south of about 25°30'N (**Figure 5.4**).

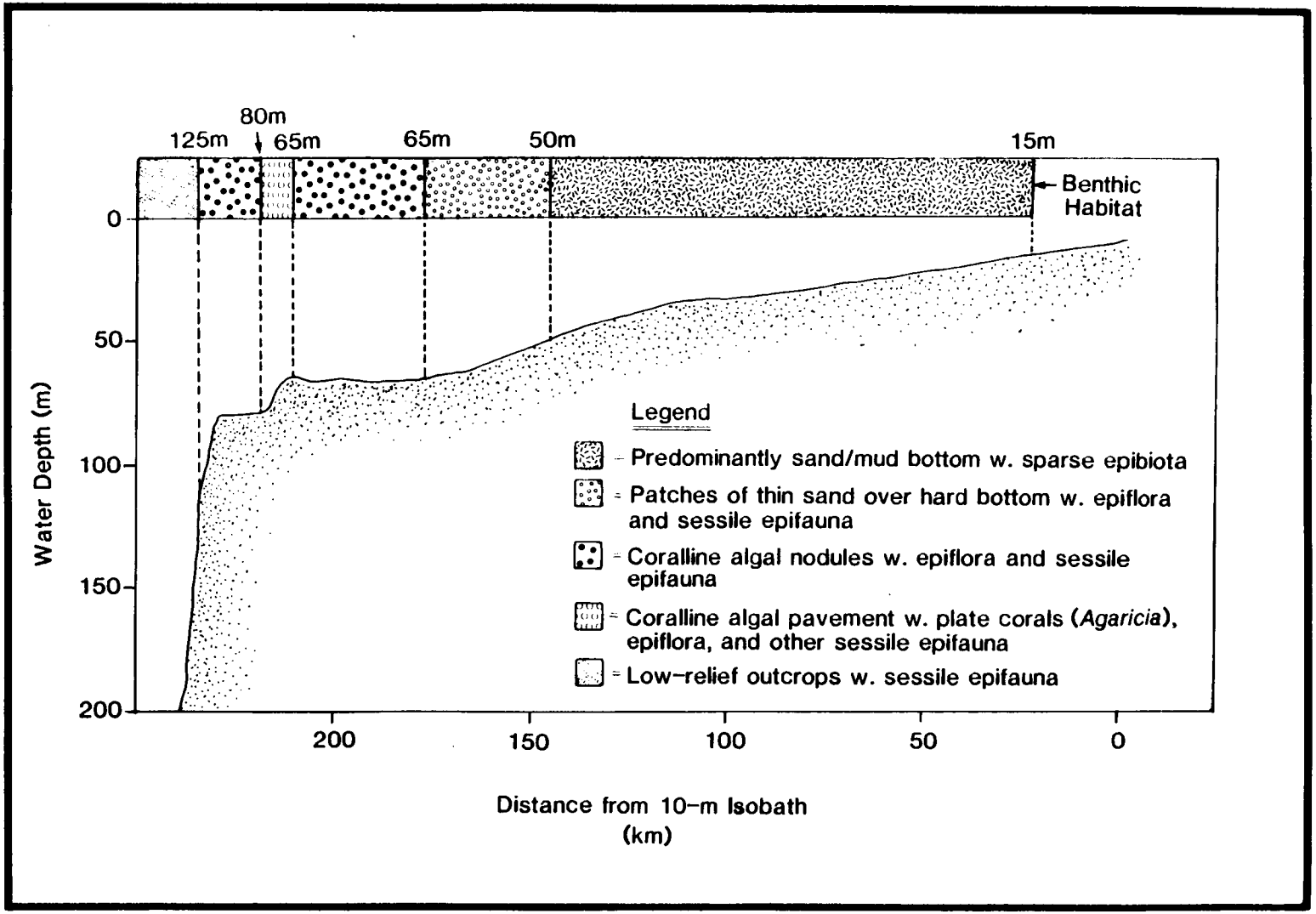

Figure 5.5. General distribution of benthic habitats on the Southwest Florida shelf at 24°48'N (north of the Dry Tortugas) (Data from: Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1985; Continental Shelf Associates, Inc. 1989).

Straits of Florida Shelf

Offshore of the bank reefs of the Florida Reef Tract, the bottom slopes gradually for several kilometers, then drops sharply to the depths of the Straits of Florida. There have been no broad-scale surveys of shelf benthic habitats in this area. However, information is available from studies in the area of the Key Largo National Marine Sanctuary (Jameson 1981) and the Looe Key National Marine Sanctuary (NOAA 1980). Observations show that a deep reef and a coralline algal rubble zone are present offshore of the shallow bank reefs, probably along the entire extent of the Florida Reef Tract. These areas are in Federal waters and would be considered live bottom under the MMS definition (see footnote 1). Other recent surveys conducted offshore the Lower Keys and Marquesas Keys show the presence of scattered hard bottom areas in Federal waters (Continental Shelf Associates, Inc. 1990).

Key Largo National Marine Sanctuary. Submersible surveys conducted off Key Largo in 1973 by Harbor Branch Foundation investigators documented the presence of a deep reef seaward of Molasses Reef (Antonius 1974). Later, deepwater habitats offshore of French Reef, The Elbow, and South Carysfort Reef were surveyed using side-scan sonar, and visual observations were made from a submersible (Jameson 1981). The deep reef was found to consist of mounds, generally 1 to 2 m in relief, interspersed with sand channels. Most of the deep reef is in water depths <36 m, but it extends to 40 m depth in some places. Characteristic biota include platelike growth forms of the corals *Agaricia lamarcki*, *Montastraea annularis*, and *M. cavernosa*, as well as the yellow pencil coral *Madracis mirabilis*, the barrel sponge *Xestospongia muta*, and various octocorals.

The relationship of the deep reef to the shallow reef differs depending on location. Jameson (1981) reported that the deep reef at French Reef is a continuous extension of the shallow reef, whereas at The Elbow, the deep reef is separated from the shallow reef by a sandy, soft coral flat lying at the base of a 12-m high, shallow reef face. At South Carysfort, the deep reef is isolated from the shallow reef by a sand flat.

At all three reefs surveyed in the Key Largo National Marine Sanctuary, a coralline algal rubble zone was found in depths of 40 to 55 m, offshore of the deep reef (Jameson 1981). This zone, which is about 1,000 m wide and at least 50 km (27 nmi) long, is characterized by leafy algae, octocorals, sponges, and small scleractinian corals such as *Manicina areolata* and *Porites* sp. (though no reef builders are present). The coralline algal rubble zone probably extends along the length of the Reef Tract (Shinn 1981). It is similar to the coralline algal nodule zone seen on the Flower Garden Banks (Bright 1981) and the Southwest Florida shelf (described in the previous section).

Offshore of the coralline algal rubble zone, from 55 m to at least 90 m, the substrate is predominantly sand bottom (Jameson 1981). Inconspicuous algae are present, as well as various soft bottom macroepifauna, including sand dollars, sea urchins, and sea stars (*Oreaster*).

Looe Key National Marine Sanctuary. Biological zonation offshore of the shallow bank reef at Looe Key has also been studied via submersible observations (NOAA 1980). A deep reef is present, beginning at 9 to 11 m depth and extending to 30 to 35 m depth, where there is a drop-off to a sandflat. The deep reef is several hundred meters in extent, and the shallower part is similar to patch reefs in species composition, with numerous octocorals and small-to-medium scleractinian corals present.

Another reef habitat, referred to as the deep ridge, occurs at about 45 m depth and is separated from the deep reef by about 1,000 m of sand bottom. This is a low-profile outcrop of living coral reef formed mainly by platelike colonies of *Montastraea cavernosa*

and several agariciid corals, which show considerable sedimentation damage (NOAA 1980). Deepwater octocorals, particularly *Ellisella barbadensis* and *Iciligorgia schrammi*, are also present, with *E. barbadensis* being much more abundant than on the deep reef. The relationship of the deep ridge to the deep reef and shallow reef at Looe Key is not known (NOAA 1980).

Lower Keys and Marquesas Keys. Continental Shelf Associates, Inc. (1990) used a towed video camera to survey three sites on the continental shelf near the Marquesas Keys in December 1989. One site was 15 km (8 nmi) south of the Marquesas in a water depth of 40 to 91 m. A second site was 24 km (13 nmi) south-southwest of the Marquesas in a water depth of 52 to 91 m. The third site was 32 km (17 nmi) west of the Marquesas in a water depth of 8 to 21 m. All three sites were predominantly sand bottom, but areas of hard bottom were occasionally observed. Most hard bottom areas had little vertical relief (<1 m), but outcrops up to 10 m in height were observed at the shallow site west of the Marquesas. Hard bottom areas at the shallow site were colonized by a dense assemblage of stony corals, octocorals, sponges, and other sessile epifauna. Hard bottom areas at the deeper sites supported less dense growths of sponges, octocorals, hydroids, and bryozoans.

Researchers from the U.S. Geological Survey (USGS) conducted seismic profiling offshore the Lower Keys and Marquesas in July 1989 (E. Shinn, pers. comm. 1989, USGS, St. Petersburg). The researchers found a spectacular deep reef complex offshore Key West, with vertical relief up to 30 m. No visual observations of the outcrops or biota were made. Additional surveys are planned for 1990.

COMMUNITY DESCRIPTIONS

This section discusses characteristics of communities associated with two major habitat types: hard bottom and soft bottom. The hard bottom discussion focuses on epibiota, whereas the soft bottom discussion includes information on macroinfauna, macroepifauna, and seagrass. Southwest Florida shelf collections are the main basis for the discussion; information on deep reef communities offshore of the Florida Reef Tract is included in the Coral Reefs section of **Chapter 4.**

Hard Bottom Communities

Most of the available information about hard bottom communities comes from six hard bottom stations sampled in the study area during the SOFLA study (**Figure 5.1**).

Macroflora and Sessile Epifauna

Abundance. Two approaches have been used to quantify the abundance of hard bottom epibiota: areal coverage estimates, and counts of individuals or colonies. For flattened organisms such as some corals, sponges, and macroalgae, the former approach is probably more useful. For erect forms such as many octocorals, counts are of more interest.

Table 5.1 summarizes bottom coverage estimates for hard bottom stations in the study area. Two types of coverage estimates are provided in the table. The first is the incidence of live bottom, which was estimated from broad-scale surveys of a 1 km^2 area at each station. This figure is the percentage of the bottom covered by dense epifaunal growth. The second number is the cover percentage derived from analysis of still photographs (generally 100) from each station. The two estimates may differ considerably because of the different scale of the observations.

Table 5.1. Bottom coverage of epibiota at Southwest Florida Shelf Ecosystems Study hard bottom stations in the study area (Adapted from: Danek and Lewbel 1986; Continental Shelf Associates, Inc. 1987a).

Station	Water Depth (m)	Incidence of Live Bottom (%)*	Cover (%)†				Major Contributors
			Spring	Summer	Fall	Winter	
52	14	79	22	–	39	–	Algae, sponges, octocorals
51	17	84	21	–	49	–	Algae, seagrass (*Halophila*), sponges, octocorals
55	27	–§	52¶	44¶	26¶	29¶	Algae, sponges, octocorals
27	54	14	12	–	8	–	Sponges, algae (*Caulerpa*, *Halimeda*)
29	64	100	80	90	64	75	Algae (*Anadyomene*, *Peyssonnelia*), stony corals (*Agaricia*)
30	76	100	50	–	48	–	Algae (*Anadyomene*, *Peyssonnelia*), sponges

* Estimated from underwater video surveys within a 1 km^2 area. Video footage was divided into 15-s intervals (about 15 m distance), and each interval was scored as "live bottom" or "not live bottom."
† Estimated by using a point overlay method on quantitative still photographs (typically 100 photographs, each 0.5 m^2 in area) from each station.
§ Not estimated for this station.
¶ Estimate includes algae and sponges only. Octocorals were abundant, but their cover was not estimated.

The incidence of live bottom at the stations shown in **Table 5.1** is high, which is not surprising, given that the stations were chosen because of dense epifaunal growth. However, the actual coverage in quantitative photographs is generally $\leq$50%, except at Station 29, which was typified by lush growth of *Anadyomene menziesii* and other algae, as well as platelike reef corals, *Agaricia* spp. Coverage may vary seasonally, especially where macroalgae account for much of the total.

Table 5.1 also indicates that octocorals accounted for a significant portion of the cover at stations in depths of 14, 17, and 27 m. The octocorals were not major cover contributors at the deeper stations.

Danek and Lewbel (1986) estimated the numerical abundance of some conspicuous sessile epifauna at stations in and near the study area. Vase sponges (*Ircinia campana*) ranged from 1.6 to over 400 colonies/ha, with the highest densities on the inner shelf (<20 m depth). Octocorals had the highest numerical abundance, ranging as high as 150,000 colonies/ha. Octocoral abundance generally declined with increasing water depth.

Biomass. Biomass estimates are available from five hard bottom stations in water depths <20 m, including two in the current study area (Continental Shelf Associates, Inc. 1987a). Total wet-weight biomass ranged from 0.7 to 4.3 kg/m^2, with a mean of about 2 kg/m^2. Sponges were the main contributor, accounting for an average of 58% of the total (wet biomass may exaggerate the importance of sponges because of their high internal volume). Stony corals, octocorals, bivalves, and macroalgae also accounted for significant portions of the total.

Biomass estimates are not available for deeper water. However, it is likely that biomass declines with increasing water depth. Some of the larger sponges (e.g., loggerheads) that contribute a large share of the biomass at the nearshore stations are less abundant in deeper waters (Danek and Lewbel 1986).

Species Composition. The species composition of hard bottom communities on the shelf varies mainly with water depth (Continental Shelf Associates, Inc. 1987a). This probably reflects changes in substrate and light levels, as well as other depth-related variables.

Hard bottom communities of the inner shelf (<20 to 25 m) are characterized by lush octocoral growth. Common genera include *Eunicea*, *Muricea*, *Plexaurella*, and *Pseudopterogorgia*. Large sponges are also seen, particularly *Spheciospongia vesparium* (loggerhead sponge), *Ircinia campana* (vase sponge), *I. felix*, *I. strobilina*, *Haliclona* sp. (finger sponge), *Cinachyra alloclada*, and *Geodia gibberosa*. Small colonies of scleractinian corals (*Cladocora arbuscula*, *Phyllangia americana*, *Siderastrea radians*, *Solenastrea hyades*, and others) also are present, though inconspicuous amongst the dense gorgonians.

The shallow-water octocoral populations decline rapidly in abundance beyond about 20 m depth, probably because of declining light levels; these octocorals contain symbiotic zooxanthellae that require light for photosynthesis. Off the Dry Tortugas, the shallow-water octocoral communities extend into deeper water (at least 27 m) because the offshore waters are clearer than those at comparable depths near the mainland. In water depths between 25 and 65 m, sponges and macroalgae are the main conspicuous epibiota associated with hard bottom areas.

A narrow portion of SOFLA transect E is characterized by an assemblage of platelike reef corals (*Agaricia* spp.) and dense growths of the green alga *Anadyomene menziesii*, occurring on a fused coralline algal pavement. Biotic coverage in this area ranges from 64 to 90%, the highest values seen on the shelf (**Table 5.2**). Most of the cover is due to algae (*Anadyomene* and *Peyssonnelia*), which vary little seasonally in their abundance at this depth.

Table 5.2. Biotic cover in bottom photographs from hard bottom Station 29 on the Southwest Florida shelf (From: Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1985).

Season	Cover (%)			
	Anadyomene (green alga)	*Peyssonnelia* (red alga)	*Agaricia** (plate coral)	All Biota
Summer (Jul-Aug 1981)	34.2	15.9	6.4	89.7
Fall (Oct-Nov 1980)	36.2	8.8	9.2	64.5
Winter (Jan-Feb 1982)	31.3	10.4	9.9	74.8
Spring (Apr-May 1981)	34.5	13.9	12.4	79.6
MEAN	34.0	12.2	9.5	77.2

* Variation in cover of *Agaricia* reflects sampling error as well as slight changes in cover of various algae, which may partially obscure the corals in the photographs.

Because of the water depth and resulting low light levels on the outer shelf, algae are not major elements of the epibiota. The dominant sessile epibiota are crinoids, antipatharians, azooxanthellate octocorals and hard corals, and small, hexactinellid (glass) sponges. The crinoids occur both on emergent rock as well as on layers of coarse shell rubble in soft bottom areas.

The following discussion provides additional information about the distribution of selected groups of epibiota on the Southwest Florida shelf.

Macroalgae: Over 160 species of macroalgae have been collected from hard bottom stations on the Southwest Florida shelf (Continental Shelf Associates, Inc. 1987a). Widely collected genera include the red algae *Gracilaria*, *Laurencia*, and *Lithothamnium*; the green algae *Caulerpa*, *Halimeda*, *Penicillus*, and *Udotea*; and the brown algae *Dictyopteris*, *Dictyota*, and *Sargassum*.

The species composition of the macroflora varies with water depth. Typical species of the inner shelf (<30 m) include *Caulerpa sertularioides*, *Gracilaria debilis*, *Halimeda scabra*, *Laurencia intricata*, and *Udotea conglutinata* (Continental Shelf Associates, Inc. 1987a). On the middle shelf (60 to 90 m depth), coralline algal nodules and algal pavements are strongly typified by a suite of crustose red algae, *Peyssonnelia rubra* and *P. simulans*, and green algae, *Anadyomene menziesii* and *Halimeda* spp. Very high densities of *A. menziesii* occur in the algal pavement areas in the 65- to 80-m depth range along SOFLA transect E. Dense meadows of *Halimeda* spp. have been reported from the 70- to 80-m depth range just north of the study area (Continental Shelf Associates, Inc. 1988a).

Algal cover on the inner shelf varies seasonally, with the highest abundances usually observed in summer. Massive blooms of species such as the brown alga *Dictyopteris* and the green alga *Codium isthmocladum* have been observed at some inner and middle shelf stations (Danek and Lewbel 1986; Continental Shelf Associates, Inc. 1987a). In general, algal cover on the middle shelf varies little seasonally, with species such as *Peyssonnelia* spp. and *Anadyomene menziesii* being present in about the same abundance year-round (**Table 5.2**). Bottom temperatures at depths between 50 and 100 m vary by only about 4 to 6 °C and generally remain above 18 °C (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1985).

Sponges: Sponges are colonial invertebrates that occur widely in hard bottom habitats, including Caribbean reefs and the Florida Reef Tract (Schmahl 1984). The Southwest Florida shelf harbors a large number of sponge species that collectively account for a large portion of the sessile epifaunal biomass in most locations, especially on the inner and middle shelf. All sponges are suspension feeders, and many also apparently contain symbiotic blue-green algae (cyanobacteria) that are analogous in function to the dinoflagellate zooxanthellae of the corals (Wilkinson 1987).

There are four classes of sponges. Most of the species on the Southwest Florida shelf belong to the Demospongea, which contain siliceous spicules and/or organic spongin fibers. This group includes common commercial sponges (sheepswool sponge *Hippospongia lachne*, and various species of *Spongia*) (Walton Smith 1954); boring sponges (e.g., *Cliona*); and some of the most conspicuous species such as the loggerhead sponge *Spheciospongia vesparium* and the vase sponge *Ircinia campana*. Class Calcarea is represented by only four genera in the Southwest Florida shelf collections (*Aphroceras*, *Clathrina*, *Leucetta*, and *Leucoselenia*). Sponges in this group contain calcareous spicules. A third group, the Hexactinellida, contains only deepwater forms (glass sponges) that contain siliceous spicules. Two species (*Aulocystis zittelii* and

Dactylocalyx pumiceus) were identified from the Southwest Florida shelf collections, along with specimens from two other genera (*Eurete* and *Hexactinella*). Many of the outer shelf specimens were not identifiable to genus or species. The fourth class, Sclerospongiae, is not represented in the Southwest Florida shelf collections (nor is it present in the Florida Reef Tract).

Sponge cover ranges from 0 to 25% in hard bottom areas of the Southwest Florida shelf. Sponge biomass ranges from 446 to 3,098 g/m^2 (wet wt) and accounts for about 58% of the total biomass of sessile epifauna (>70% at some stations) (Continental Shelf Associates, Inc. 1987a).

At least 93 sponge species were collected by dredge during the SOFLA studies. Many additional specimens were identified only to genus or higher levels. The largest numbers of sponge species were collected at two middle shelf stations (15 and 21) near the study area, and at four inner shelf stations, including two in the study area (51 and 52). The fewest species were identified from the outer shelf stations, partly because of taxonomic problems.

Well-defined zonation patterns are not evident for sponges. Several species, such as *Euryspongia rosea*, *Hemectyon pearsei*, and *Thalysias juniperina*, are restricted to the inner shelf (<20 m). Most of the remaining species range from the inner to middle shelf (to 60 or 70 m depth). Examples of widely distributed species in this category are *Cinachyra alloclada*, *Geodia gibberosa*, *Haliclona compressa*, *Ircinia campana*, and *Placospongia melobesioides*. Few species occur on the outer shelf, although several unidentified hexactinellids have been collected. Of the common inner and middle shelf species, only *Ircinia strobilina* also occurs on the outer shelf.

Octocorals: The subclass Octocorallia (Alcyonaria) includes sessile invertebrates such as sea fans, sea pens, sea plumes, and sea whips. Most are associated with reef environments. These organisms typically feed on zooplankton and particulate organic matter (Lasker 1981), but most shallow-water species possess symbiotic zooxanthellae and derive some portion of their nutrition from photosynthesis. See the Coral Reefs section in **Chapter 4** for additional information on octocoral biology.

Along the mainland coast of Southwest Florida, the octocorals are most abundant in shallow water depths (<20 m). Smith (1976) reported that gorgonian densities generally are much higher at patch reefs in water depths <18 m than at deeper reefs. On the Southwest Florida shelf, octocoral abundance generally declines with increasing water depth. Gorgonian densities decrease sharply seaward of the 20-m isobath; the increase on the outer shelf reflects an increased abundance of groups such as the ellisellids, which lack zooxanthellae and are therefore not dependent on light levels. The highest nearshore densities are in the low end of the range of values reported by Goldberg (1973) for lush gorgonian beds on patch reefs off the Southeast Florida coast.

Characteristic nearshore octocoral species are *Eunicea calyculata*, *Muricea elongata*, *M. laxa*, *Plexaurella fusifera*, *Pseudopterogorgia acerosa*, and *Pterogorgia guadalupensis*. Many of these species extend to greater depths (at least 27 m) near the Dry Tortugas (Danek and Lewbel 1986). Several additional gorgonians such as *E. clavigera*, *E. laciniata*, *E. palmeri*, *E. pinta*, *Plexaura homomalla*, *Pterogorgia anceps*, and *Pterogorgia citrina* occur in this area.

All of these nearshore gorgonian species harbor symbiotic zooxanthellae and derive at least part of their nutrition from photosynthesis. Consequently, decreasing light availability with increasing water depth probably is a major factor responsible for their

limitation to shallow water depths (Goldberg 1973). However, some shallow-water species grow well when transplanted to deeper water, suggesting that effects of light levels on zonation may be due to larval preference or differential larval survival rather adult survival patterns (Goldberg 1970). Light levels are affected by water clarity as well as depth *per se*, as shown by the occurrence of large numbers of zooxanthellate gorgonians at 27 m near the Dry Tortugas. Away from the mainland coast with its turbid waters, the gorgonians apparently are able to live at greater depths.

Zonation patterns on the middle and outer shelf are not as well defined. Octocoral densities are much lower than in the nearshore zone, and the species lack zooxanthellae. Examples of widely distributed middle shelf species are *Lophogorgia cardinalis* (19 to 77 m), *Diodogorgia nodulifera* (30 to 76 m), and *Telesto sanguinea* (30 to 77 m). Common middle to outer shelf species include *Ellisella barbadensis* (50 to 159 m), *Scleracis guadalupensis* (62 to 159 m), and *Siphonogorgia agassizi* (77 to 159 m). Species apparently restricted to the outer shelf include *Nicella* cf. *granifera*, *Placogorgia mirabilis*, and *Thesea grandiflora*.

Stony corals: Fifty-nine species of stony corals have been collected from the Southwest Florida shelf in and near the study area. Most of those collected on the inner and middle shelf contain symbiotic zooxanthellae and presumably derive most of their nutrition from photosynthesis. However, there is little reef-building activity (light-enhanced calcification) with the exception of the deep *Agaricia* reef found in the vicinity of Station 29. Accordingly, these corals are referred to as zooxanthellate rather than hermatypic (Schuhmacher and Zibrowius 1985).

Table 5.3 lists the scleractinian species that were collected at one or more of the SOFLA stations; for comparison, corals reported from the Florida Reef Tract (see **Chapter 4**) are included. Of 59 species reported from the Florida Reef Tract, 32 have been collected on the Southwest Florida shelf. Twenty-seven species have been found on the shelf but not in the Reef Tract, including mostly representatives of deepwater families such as Caryophylliidae and Flabellidae. Major hermatypic (reef-building) species such as *Acropora cervicornis*, *A. palmata*, *Colpophyllia natans*, *Diploria labyrinthiformis*, *D. strigosa*, and *Montastraea annularis* have not been collected on the Southwest Florida shelf. Many of the more common corals on the inner and middle shelf are hardy, tolerant species that are often found in some of the less favorable, fringing environments in Caribbean and South Florida coral reef systems (Jaap 1984).

Different suites of stony coral species are associated with hard bottom habitats in different depth ranges. *Cladocora arbuscula*, *Phyllangia americana*, *Scolymia lacera* *Siderastrea radians*, *Solenastrea hyades*, and *Stephanocoenia michelinii* are typical of inner shelf hard bottom areas (depths <40 to 50 m). All but *P. americana* contain symbiotic zooxanthellae (Cairns 1977, 1978) and may be light-limited in their distribution. *Phyllangia americana* also occurs on the outer shelf to a depth of at least 159 m. Most of the inner shelf species are also fairly tolerant of exposure to suspended solids and temporary (several days) burial (Rice 1984). Hubbard and Pocock (1972) reported that *Isophyllia sinuosa* and *Manicina areolata*, two additional species found on the inner and middle shelf, can right themselves after being overturned in sediment.

Near the Dry Tortugas in a water depth of 27 m, Station 55 harbored a diversity of hard corals, including one species (*Meandrina meandrites*) not found at any of the other stations (though believed to occur more widely). Station 55 was second to Station 29 in the number of coral species collected (15 *vs.* 19), and several deep reef species were found only at these two stations (e.g., *Leptoseris cucullata*, *Madracis decactis*, and *Montastraea cavernosa*).

Table 5.3. Scleractinian corals of the Southwest Florida shelf vs. those of the Florida Reef Tract. Southwest Florida data are from Environmental Science and Engineering, Inc. et al. (1987) and W. Jaap (pers. comm. 1989, Florida Department of Natural Resources, St. Petersburg). Florida Reef Tract data are from Jaap and Hallock (**Chapter 4**).

Species	Southwest Florida Shelf	Florida Reef Tract	Species	Southwest Florida Shelf	Florida Reef Tract
Acropora cervicornis		x	*Isophyllia sinuosa*	x	x
Acropora palmata		x	*Javania cailleti*	x	
Acropora prolifera		x	*Leptoseris cucullata*	x	x
Agaricia agaricites danai		x	*Madracis asperula*	x	
Agaricia agaricites purpurea	x	x	*Madracis brueggemanni*	x	
Agaricia agaricites carinata		x	*Madracis decactis*	x	x
Agaricia agaricites	x	x	*Madracis formosa*	x	x
Agaricia fragilis	x	x	*Madracis mirabilis*	x	x
Agaricia lamarcki	x	x	*Madracis myriaster*	x	
Agaricia undata		x	*Madrepora carolina*	x	
Anomocora fecunda	x		*Madrepora oculata*	x	
Astrangia poculata	x	x	*Manicina areolata*	x	x
Astrangia solitaria	x	x	*Manicina areolata mayori*		x
Balanophyllia floridana	x	x	*Meandrina meandrites brasiliensis*		x
Balanophyllia wellsi	x		*Meandrina meandrites*	x	x
Caryophyllia ambrosia caribbeana	x		*Montastraea annularis*		x
Caryophyllia berteriana	x		*Montastraea cavernosa*	x	
Caryophyllia cornuformis	x		*Mussa angulosa*	x	x
Caryophyllia horologium	x		*Mycetophyllia aliciae*		x
Cladocora arbuscula	x	x	*Mycetophyllia danaana*		x
Cladocora debilis	x		*Mycetophyllia ferox*		x
Coenosmilia arbuscula	x		*Mycetophyllia lamarckiana*		x
Colpophyllia amaranthus		x	*Oculina diffusa*	x	x
Colpophyllia breviseralis		x	*Oculina robusta*	x	
Colpophyllia natans		x	*Oculina tenella*	x	
Concentrotheca laevigata	x		*Oxysmilia rotundifolia*	x	
Deltocyathus calcar	x		*Paracyathus pulchellus*	x	x
Deltocyathus eccentricus	x		*Phyllangia americana*	x	x
Dendrogyra cylindrus		x	*Porites astreoides*	x	x
Dendrophyllia cornucopia	x		*Porites branneri*	x	x
Dendrophyllia gaditana	x		*Porites porites clavaria*		x
Dichocoenia stellaris	x	x	*Porites porites furcata*		x
Dichocoenia stokesii		x	*Porites porites divaricata*	x	x
Diploria clivosa		x	*Porites porites*	x	x
Diploria labyrinthiformis		x	*Rhizosmilia maculata*	x	
Diploria strigosa		x	*Scolymia cubensis*		x
Eusmilia fastigiata		x	*Scolymia lacera*	x	x
Favia fragum		x	*Siderastrea radians*	x	x
Favia gravida	x	x	*Siderastrea siderea*	x	x
Flabellum fragile	x		*Solenastrea bournoni*	x	x
Guynia annulata	x		*Solenastrea hyades*	x	x
Isophyllastraea rigida		x	*Stephanocoenia michelinii*	x	x
Isophyllia multiflora	x	x	*Trochocyathus rawsonii*	x	

Few coral species are found in the 45- to 60-m depth range, probably due to declining light levels and limited availability of suitable substratum for zooxanthellate species able to grow under low light (e.g., agariciids). *Oculina tenella*, an azooxanthellate species, occurs most consistently in this depth range.

In the 62- to 77-m depth range, three species of *Madracis--M. brueggemanni*, *M. formosa*, and *M. mirabilis*--are associated with substrates of dense algal nodules and algal nodule pavement. Station 29 possessed the largest and most distinctive coral assemblage, consisting of 19 species, including a number of deep reef corals. Species found primarily or exclusively at this station included the agariciids *Agaricia agaricites*, *A. fragilis*, *A. lamarcki*, and *Leptoseris cucullata*, as well as *Madracis decactis*, *Montastraea cavernosa*, and *Porites astreoides*. Only one of the agariciids was collected at Station 30, which also was characterized by the algal nodule pavement but at a greater water depth than Station 29 (76 m vs. 62 m).

Another area of *Agaricia* growth was seen during surveys of a transect southwest of the Dry Tortugas, although no still photographs or specimens were collected there (Danek and Lewbel 1986). The location of this area is shown on **Figure 5.4.** Also, a similar suite of species has been reported from the deep reef offshore of the Florida Reef Tract (Jameson 1981).

The predominance of agariciids at Station 29 probably reflects the influence of both light levels and substratum type. The platelike growth form of *Agaricia* optimizes light capture, allowing the corals to grow at depths greater than those inhabited by most zooxanthellate species. Decreasing light availability probably defines the lower depth limit of the agariciid reef growth. Also, the absence of unconsolidated sediments at Station 29 is an important factor, because *Agaricia* is not capable of removing large amounts of coarse sediment (Hubbard and Pocock 1972). In Caribbean and South Florida reefs, *Agaricia* may occur in turbid environments, but the colonies are usually angled to slough off sediment (e.g., colonies occur on vertical surfaces and undersides of ledges) (Hubbard and Pocock 1972; Jaap 1984).

The outer shelf is characterized by a suite of azooxanthellate forms, primarily species in the families Caryophylliidae and Flabellidae. *Caryophyllia berteriana*, *C. horologium*, *Deltocyathus calcar*, *Flabellum fragile*, *Javania cailleti*, *Paracyathus pulchellus*, and *Trochocyathus rawsonii* all are solitary. *Paracyathus pulchellus* was cited as a common deepwater species in MAFLA samples from all areas of the West Florida shelf (Hopkins 1979). *Caryophyllia horologium*, previously reported to a depth of 91 m in the Hourglass samples, may occur attached to the hard substratum or as a free surface-dweller, along with *D. calcar* and *T. rawsonii* (Cairns 1977). Nearly all of the species that are common on the outer shelf occur exclusively there.

Crinoids: Comatulid crinoids (feather stars) are conspicuous elements of the outer shelf epifauna. Feather stars are discretely motile rather than sessile; the organisms can swim, and they attach by means of their basal cirri to various substrata, such as rock, shell, and other animals. Nutrients are derived via suspension feeding.

Common species on the Southwest Florida shelf are *Comactinia meridionalis*, *Crinometra brevipinna*, *Leptonemaster venustus*, and *Neocomatella pulchella*. All but *C. meridionalis* are limited to the outer shelf (depths >100 m). The crinoids are typically associated with exposed hard bottom as well as areas of coarse shell rubble.

The average crinoid density at one outer shelf station near the study area (127 m water depth) has been estimated at 3 individuals/m^2 (Danek and Lewbel 1986). This

was considered to be a dense crinoid population. The substratum at this station consisted of coarse sand and shell rubble.

Environmental Influences. The Southwest Florida shelf supports a diverse sessile epibiota. Likely contributing factors are the large area of the shelf, the range of water depths and substratum types represented, the generally favorable temperature regime for tropical and subtropical species, and the proximity to sources of colonizing reef biota.

The apparent importance of water depth as a master variable controlling zonation patterns of the major faunal groups undoubtedly reflects the influence of correlated environmental variables such as temperature, light, and substratum type. Zonation patterns that appear related to factors other than water depth alone (e.g., the occurrence of *Agaricia* between 65 and 80 m in the current study area but not farther north in the same depth range) probably reflect non-depth-related variations in these underlying controlling factors.

Temperatures on most of the shelf are suitable most of the time for tropical species to flourish. Except for locations on the outer shelf, temperatures are greater than 18 °C most of the time (Danek and Lewbel 1986). Inner shelf temperatures are more seasonally variable than middle and outer shelf temperatures, however, and occasional cold fronts may kill large numbers of tropical invertebrates and fishes in shallow water (Bullock and Smith 1979; Bohnsack 1983). Temperatures on the outer shelf may also be too low for tropical species, at times, due to upwelling of cold water from the continental slope, which can result from Loop Current intrusions (Woodward-Clyde Consultants and Skidaway Institute of Oceanography 1983). Therefore, the middle shelf probably is the most favorable for development of tropical assemblages.

Light is another important influence on the composition of sessile epifaunal communities. As noted previously, many of the corals and sponges present on the shelf contain symbiotic algae and depend, in part, upon photosynthesis to meet their nutritional requirements. Illumination decreases with increasing water depth, with the 1% (of surface incident) light level occurring at approximately 65 to 70 m on the Southwest Florida shelf (Woodward-Clyde Consultants and Skidaway Institute of Oceanography 1983). Species that depend upon symbiotic zooxanthellae are restricted to the inner and middle shelf; the bathymetric ranges of individual taxa differ depending on their adaptations to the light regime. Water column turbidity also affects the amount of light reaching the benthos, and nearshore areas are subject to episodic resuspension events that severely cloud the water. Nearshore species must be able to tolerate intermittent turbidity.

For sessile epifauna, the availability of suitable hard substratum for attachment is often a limiting factor. On the Southwest Florida shelf, this is particularly important because there is very little exposed hard bottom and most is of low relief (<1 m). Most areas of hard bottom are covered by a thin sand veneer, but the underlying rock must occasionally be exposed in order for larvae to attach and grow fast enough so as not to be smothered when the area is again covered by sand. Where the sand veneer is thin and the potential for sediment movement is high, exposure and colonization of hard bottom must be relatively frequent, and one would expect to find extensive growths of sessile epibiota in such areas. This appears to be true both on a local scale (biomass and cover of sessile epifauna are greater at stations where the veneer is thick than where it is thin) and on a regional scale (live bottom associated with sand-covered hard bottom is most common on the inner shelf [<20 m] where the sand veneer is generally thin and the potential for sediment movement by surface waves is high).

Latitudinal differences in substratum type help to explain why *Agaricia* predominates in the 65- to 80-m depth range south of 25°N but not at locations in the same depth range to the north. The algal nodule pavement present in this area provides a favorable environment for growth of *Agaricia*, which does not tolerate high sediment loading. Why the pavement develops in this area and not farther north is unknown, but temperature, nutrients, and hydrodynamics probably are major influences. The density of algal nodules generally increases from north to south in this depth range, possibly reflecting slightly higher temperatures and higher near-bottom nutrient levels toward the south (due to upwelling-induced doming of nutrient contours near the shelf break, which is steeper in the southern part of the study area). Also, nodules require particular hydrodynamic conditions for their formation. The incipient nodules form on bits of shell debris or other nuclei, and periodic rolling of the growths is necessary for the formation of spheroid or ovoid shapes (Bosellini and Ginsburg 1971). Rolling may be accomplished by surface waves during storms (not a major influence at these depths, except perhaps during a hurricane) or even by movement of sand waves, as suggested by McMaster and Conover (1966). Slightly more quiescent hydrodynamic conditions usually associated with increasing water depth can result in increasingly flattened or amoeboid growth, or ultimately, a flattened pavement.

Motile Epifauna

Hard bottom areas on the continental shelf support a diverse motile epifauna. During the SOFLA study, at least 306 species of molluscs, 283 species of crustaceans, and 120 species of echinoderms were collected (Continental Shelf Associates, Inc. 1987a). Many of the species have also been reported from hard bottom habitats in the South Atlantic Bight by Wenner et al. (1983).

Most large species of motile epifauna on the shelf are sand dwellers that are either restricted to or most abundant on sand, whether or not it is adjacent to rock outcrops or other hard substrate (Environmental Science and Engineering, Inc. et al. 1987). Examples include various species of sea stars, sea urchins, holothurians, portunid and calappid crabs, and conchs. Species more closely associated with high-relief hard bottom include palinurid and scyllarid lobsters (*Panulirus argus*, *P. guttatus*, *Scyllarides* spp., and *Scyllarus* spp.), brachyuran crabs (*Stenocionops furcata* and others), and some sea urchins (*Arbacia punctulata*, *Diadema antillarum*, and *Eucidaris tribuloides*). Because many of these species are partially or wholly herbivorous, they tend to be more abundant in shallower water where plants are more readily available.

In addition to the large motile epifauna, there are numerous smaller species that live in or on larger sessile epifauna such as sponges and octocorals, or in crevices and holes where there is exposed hard bottom. For example, the brittle star *Ophiothrix angulata* is associated with shallow-water octocoral species and reaches densities of 1 to 2 individuals/m^2 (Continental Shelf Associates, Inc. 1987a). Numerous synalpheid shrimps (e.g., *Synalpheus minus*, *S. pandionis*, and *S. townsendi*), polychaete worms (e.g., *Haplosyllis spongicola*), and other organisms inhabit sponges or other sessile epifauna. The diversity and abundance of these smaller motile epifauna are made possible by the presence of the larger, sessile species, which provide shelter and in some cases, food.

At least 220 fish species have been collected from the Southwest Florida shelf (Continental Shelf Associates, Inc. 1987a). Frequently collected species include fringed filefish, *Monacanthus ciliatus*; sand diver, *Synodus intermedius*; offshore lizardfish, *Synodus poeyi*; barbfish, *Scorpaena brasiliensis*; and dusky flounder, *Syacium papillosum*. Many other species, including numerous primary reef fishes (Starck 1968), occur in hard bottom areas such as the deep *Agaricia* reef at SOFLA Station 29. These species are

not readily sampled by trawling, but can be quantified by visual observations (Danek and Lewbel 1986). Fish populations are discussed further in **Chapter 7.**

The species composition of the motile epifauna on the Southwest Florida shelf varies primarily with water depth or related variables (Lyons 1979; Continental Shelf Associates, Inc. 1987a). For crustaceans, the major break in species composition is at about 40 m depth, whereas for echinoderms and molluscs, the break appears to be at about 60 m (Continental Shelf Associates, Inc. 1987a).

Soft Bottom Communities

Macroinfauna

Continental shelf environments typically support a diverse macroinfauna consisting of many species, most represented by a few individuals in a given collection (Rabalais and Boesch 1987). Polychaetes and peracarid crustaceans usually account for most of the individuals and species. Rarely does any species account for more than 10 to 15% of total abundance, although opportunistic species may be locally abundant. The macroinfauna of the Southwest Florida shelf appear to fit this pattern. An additional characteristic of this shelf is the widespread occurrence of hard substrates such as shell rubble and coralline algal rubble, which can result in high numbers of syllid polychaetes (motile carnivore/scavengers) near areas of dense, sessile epifaunal growth.

There are two main sources of information concerning Southwest Florida shelf macroinfauna: the MAFLA study sponsored by the BLM and the SOFLA study funded by the MMS. Data from the latter study are the main basis for this discussion.

Macroinfaunal stations occupied during the SOFLA study are shown in **Figure 5.1.** Twenty-nine stations, including seven in the study area, were sampled two or four times between 1980 and 1984. Water depths ranged from 10 to 148 m. Methods and results are summarized by Environmental Science and Engineering, Inc. et al. (1987).

Several MAFLA stations were sampled on the Southwest Florida shelf between 1975 and 1978, but none are in the current study area. MAFLA macroinfaunal results are summarized by Blake (1979) (molluscs), Heard (1979) (crustaceans), and Vittor (1979) (polychaetes) in chapters within the final MAFLA report (Dames & Moore 1979). Additional information on molluscs is provided in a master's thesis by Bishof (1980). Barry A. Vittor & Associates, Inc. have subsequently reanalyzed MAFLA and SOFLA polychaete samples to standardize taxonomy of this important group, but no report is available (B. Vittor, pers. comm. 1989).

Abundance. Macroinfaunal abundances on the shelf typically range from about 1,000 to 14,000 individuals/m^2 and decrease with increasing water depth (**Figure 5.6**) (Environmental Science and Engineering, Inc. et al. 1987). In the study area, there are no macroinfaunal data from waters deeper than 59 m. Coralline algal nodules and algal pavements in water depths of 65 to 125 m make infaunal sampling difficult or impossible. In deeper waters, the bottom is steep and bedrock is frequently exposed or covered by a thin sand veneer.

Polychaetes, crustaceans, and molluscs accounted for 64%, 17%, and 10%, respectively, of the macroinfaunal individuals collected during the SOFLA study (Environmental Science and Engineering, Inc. et al. 1987). The average abundance of all three groups declined with increasing water depth, but polychaetes accounted for an increasing percentage of the total as water depth increased.

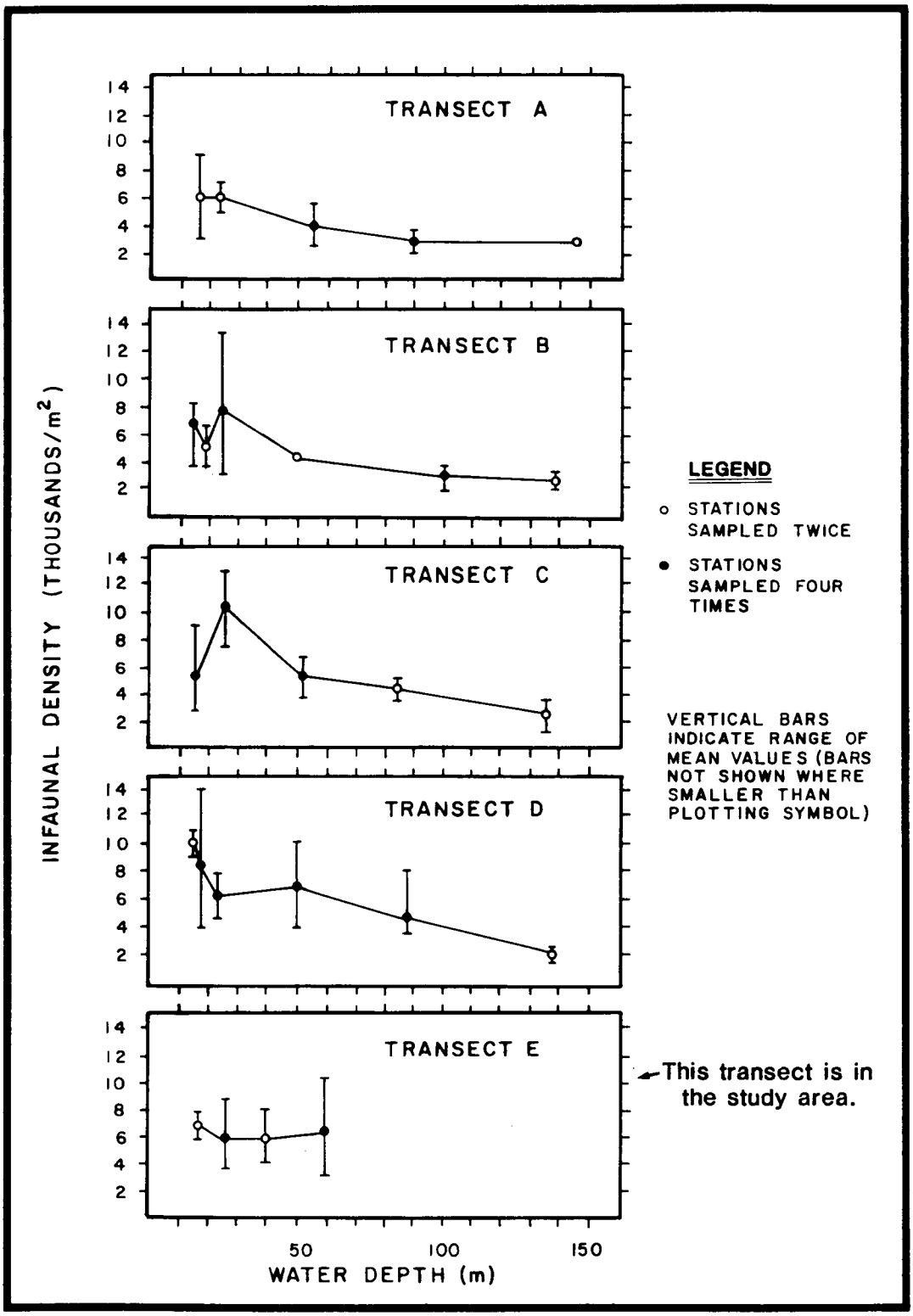

Figure 5.6. Relationships between macroinfaunal density and water depth along five east-west transects on the Southwest Florida shelf (From: Environmental Science and Engineering, Inc. et al. 1987).

Populations of some macroinfaunal populations can be expected to vary seasonally, even in the subtropical climate of the study area. No stations were occupied more than twice in a given year during the SOFLA study, making it difficult to recognize or substantiate seasonal patterns. However, abundances were generally highest during summer (Environmental Science and Engineering, Inc. et al. 1987).

Blake (1979) reported that densities of macroinfaunal molluscs were highly variable seasonally at the shallowest MAFLA station near the study area (11 m depth near Sanibel Island). The timing of peak abundances of bivalves such as *Parvilucina multilineata* and *Tellina versicolor* suggested that recruitment occurs during spring or early summer (Blake 1979). This seasonal variation at nearshore (<20 m) stations was also evident during the SOFLA study, when abundances of several bivalve species (e.g., *Crenella divaricata*, *Diplodonta punctata*, *Lucina nassula*, and *Tellina versicolor*) were much greater during spring (May 1983) than during fall (December 1982) (Continental Shelf Associates, Inc. 1987a). However, the pattern was not repeated the following year (Environmental Science and Engineering, Inc. et al. 1987).

Data from the SOFLA study do not reveal any relationships between total macroinfaunal abundance and sediment variables such as mean grain size, silt/clay percentage, carbonate content, or organic carbon content (Environmental Science and Engineering, Inc. et al. 1987). In contrast, Vittor (1979) indicated that polychaete density was generally lowest at the MAFLA stations characterized by the finest sediments. However, those stations were located in the northern Gulf of Mexico off Alabama and Mississippi, where the sedimentary regime is heavily influenced by the Mississippi River outflow. In the current study area, the finest sediments are calcareous silts and muds in the vicinity of the Dry Tortugas.

Biomass. Macroinfaunal biomass was not estimated during the SOFLA study. However, polychaete biomass was estimated in the MAFLA samples from the Southwest Florida shelf. Wet-weight biomass at these stations ranged from 0.3 to 212.4 g/m^2, with most values <20 g/m^2 (Vittor 1979). Polychaete biomass (averaged over three 1977 and 1978 samplings) generally decreased with increasing water depth. The polychaete biomass off Southwest Florida is in the low end of the range of values reported from shelf environments off the U.S. Mid-Atlantic and South Atlantic coasts (Boesch 1979; Tenore 1979; Hanson et al. 1981).

Species Richness and Diversity. At least 1,121 species were identified during the SOFLA study (Continental Shelf Associates, Inc. 1987a). Crustaceans accounted for the largest single percentage of the total (452 species, 40%), followed by polychaetes (413 species, 37%), and molluscs (231 species, 21%). About 53% of the mollusc species were bivalves. Polychaetes accounted for about 45% of the total number of species in all depth ranges except on the outer shelf, where they accounted for 60%.

Shannon-Weaver diversity values for SOFLA infaunal stations ranged from 1.66 to 4.39, with most values in the 3.00 to 4.00 range (Continental Shelf Associates, Inc. 1987a). Equitability values ranged from 0.41 to 0.87, with most values >0.70. In general, individuals were most equitably apportioned among species at stations in the <20-m and 50- to 60-m depth ranges. Equitability was not significantly correlated with sediment composition variables (mean grain size, sorting, carbonate content) within the SOFLA data set. In general, the high equitability values reflect a lack of dominance in shelf macroinfaunal populations. The most abundant species in a sample usually accounts for <15% of the total abundance. However, some species, such as the polychaetes *Filograna implexa*, *Haploscoloplos* sp., *Prionospio cristata*, and *Synelmis albini*, can account for a higher portion of the total at particular locations or during particular

seasons. For example, *Mediomastus californiensis* and *Paraprionospio pinnata* together accounted for 75% of the total population at a nearshore station off Charlotte Harbor during December 1982 (Continental Shelf Associates, Inc. 1987a).

Species Composition. **Table 5.4** lists the 25 most abundant macroinfaunal species on the Southwest Florida shelf. Most of the species were widely distributed. The most abundant species, the polychaete *Prionospio cristata*, occurred at most stations in water depths <100 m but was most abundant in water depths of 23 to 26 m. The polychaete *Synelmis albini* occurred at nearly all stations and was most abundant in water depths of 52 to 90 m. *Mediomastus californiensis*, a capitellid polychaete, was most abundant at about 20 m depth, although it occurred at all stations. *Paraprionospio pinnata* occurred widely at stations in <100 m depth (often with *Prionospio cristata* and *M. californiensis*) but was most abundant at two 18 m stations. Species with high, localized abundance include *Filograna implexa*, a gregarious serpulid that was present in dense aggregations at a few middle and outer shelf stations during summer; and *Ceratonereis irritabilis*, a nereid polychaete that was very abundant on the inner shelf (Station 52) during spring.

Table 5.4. Most abundant infaunal species on the Southwest Florida shelf (From: Environmental Science and Engineering, Inc. et al. 1987).

Species*	Number of Stations	Grand Mean Abundance (No./m^2)	Life Mode†	Feeding Type§
Prionospio cristata (P)	26	334	T	DF/SF
Synelmis albini (P)	29	314	B	C/S
Mediomastus californiensis (P)	30	160	B	DF
Paraprionospio pinnata (P)	25	142	T	DF/SF
Armandia maculata (P)	30	112	B	DF
Cirrophorus americanus (P)	26	109	B	DF
Myriochele oculata (P)	30	108	T	DF
Filograna implexa (P)	8	91	T	SF
Aricidea fragilis (P)	24	84	B	DF
Haplosyllis spongicola (P)	21	83	F	C/S
Lucina radians (B)	12	79	B	SF
Prionospio cirrifera (P)	23	67	T	DF/SF
Cyclaspis sp. A (C)	20	66	B	DF
Goniadides carolinae (P)	15	66	B	C/S
Magelona pettiboneae (P)	18	62	B	DF
Lumbrineris verrilli (P)	25	48	F	C/S
Leptochelia sp. A (T)	21	47	B	C/S
Aricidea catherinae (P)	26	44	B	DF
Levinsenia gracilis (P)	19	43	B	DF
Axiothella sp. A (P)	28	42	T	DF
Ceratonereis irritabilis (P)	4	42	F	C/S
Aricidea taylori (P)	18	41	B	DF
Ceratocephale oculata (P)	21	41	F	C/S
Sigambra tentaculata (P)	18	41	B	C/S
Tharyx annulosus (P)	28	39	F	DF

* Taxonomic groups: B = bivalve, C = cumacean, P = polychaete, T = tanaid.
† Life modes: B = burrower, T = tube dweller, F = free surface dweller.
§ Feeding Types: C/S = carnivore/scavenger, DF = deposit feeder, SF = suspension feeder.

Most of the species listed in **Table 5.4** are polychaetes. Particularly well represented is the polychaete family Paraonidae (*Aricidea catherinae, A. fragilis, A. taylori, Cirrophorus americanus*, and *Levinsenia gracilis*). The paraonids, as well as other species on the list such as *M. californiensis* and *Armandia maculata*, are burrowing, subsurface deposit feeders. Spionids, which typically are tubicolous, surface deposit feeders or suspension feeders, are also well represented (*Paraprionospio pinnata, Prionospio cirrifera*, and *Prionospio cristata*).

Macroinfaunal species composition varies with water depth, as indicated by the results of cluster analysis from the SOFLA study (**Figure 5.7**) (Environmental Science and Engineering, Inc. et al. 1987). Stations can be grouped into three depth ranges: 10 to 23 m, 24 to 48 m, and 52 to 148 m. Depth-related clustering is also evident within the middle to outer shelf group. Similar results were noted in the MAFLA study (Blake 1979; Heard 1979; Vittor 1979).

Five middle to outer shelf stations that were sampled during summer 1981 grouped across depth contours in the cluster analysis (see shaded area in **Figure 5.7**). A contributing factor was the high relative abundance of the serpulid polychaete *Filograna implexa* at those stations during summer. Two stations near Charlotte Harbor were characterized by a high degree of temporal variability in species composition, and other inner shelf stations also showed considerable temporal variability.

Environmental Influences. Water depth and sediment silt content (4- to 62-μm fraction) are the environmental variables that best explain the observed pattern of species composition (Environmental Science and Engineering, Inc. et al. 1987). The influence of water depth is evident in the station groupings (**Figure 5.7**). The influence of the silt fraction is indicated on the figure by the mean silt content values next to each station. Low silt content at Station 20 helps to explain why it clustered with shallower stations rather than with those in its depth range.

The area north of the Dry Tortugas is characterized by sediments with 60% silt and over 90% carbonate content (see **Figure 5.4** for general extent of this area). High silt apparently does not result in high macroinfaunal abundance, because the organic content of the sediments is low. Also, although the sediments in this area differ from those in the same depth range to the north, macroinfaunal populations at the two SOFLA stations in this area (Stations 25 and 26) are more similar to those at other stations in their respective depth ranges than to each other. This indicates that the silty sediment does not support a distinct macroinfaunal community. Station 25 was characterized by a seasonally consistent assemblage consisting primarily of the polychaetes *Magelona pettiboneae, Mediomastus californiensis, Prionospio cristata*, and *P. cirrifera*; these species accounted for 35 to 40% of total abundance on all four sampling dates. *Prionospio cristata* was among the most abundant species collected at Station 26, but other species, such as the bivalves *Caecum pulchellum* and *Lucina radians* and the polychaete *Sigambra tentaculata*, were also major contributors, and the assemblage was not as consistent seasonally. The bivalve *L. radians* was not abundant at Station 25.

The factor that most likely controls abundance and biomass is food availability. Most of the infauna of the Southwest Florida shelf are deposit feeders or suspension feeders (**Table 5.4**). Both types depend on supplies of particulate organic matter from phytoplankton production in the overlying water column. In terms of phytoplankton primary production, the shelf can be categorized as oligotrophic (Woodward-Clyde Consultants and Skidaway Institute of Oceanography 1983). Sediment trap data collected during the SOFLA study show that the deposition rate of particulate organic material declines rapidly with increasing water depth (Danek and Lewbel 1986). Thus, the decline in abundance and biomass of infauna with increasing water depth may reflect the concurrent decline in allochthonous food inputs. Autochthonous food supplies such as benthic microalgae (which many deposit feeders also consume) also presumably decline in abundance with increasing water depth due to light attenuation.

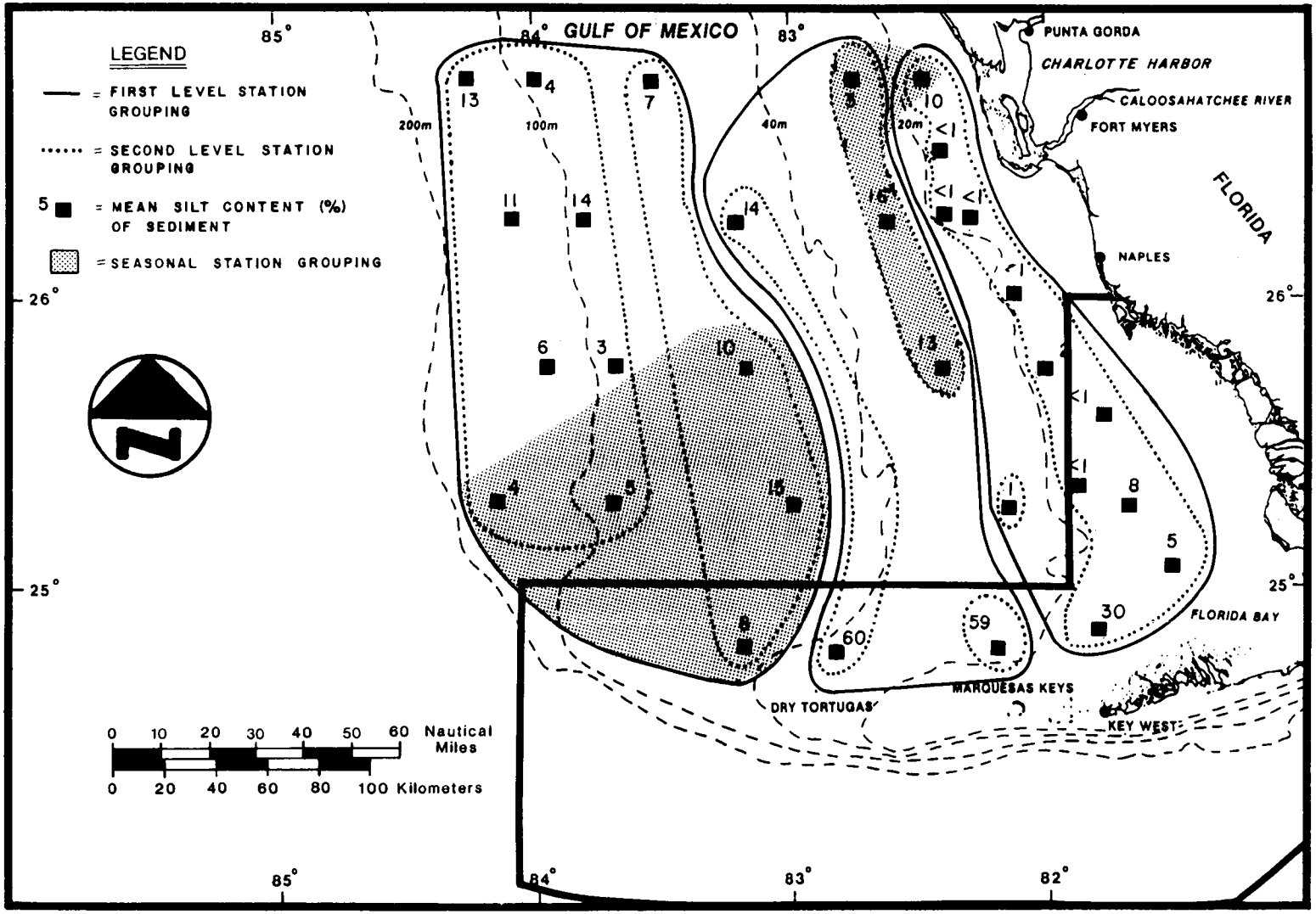

Figure 5.7. Cluster analysis results for infaunal data from the Southwest Florida shelf (From: Environmental Science and Engineering, Inc. et al. 1987). The heavy, solid line is the study area boundary for this synthesis.

Many species of infauna on the continental shelf are opportunists that are able to respond to suddenly favorable conditions such as a pulse of food. Transient primary productivity events in the water column associated with Gulf Stream meanders may be a source of food pulses to benthos on the continental shelf off the U.S. South Atlantic coast (Hanson et al. 1981). On the Southwest Florida shelf, Loop Current intrusions have been shown to produce similar, transient increases in water column primary productivity (Woodward-Clyde Consultants and Skidaway Institute of Oceanography 1983), and could provide sporadic inputs of food to deposit-feeding and suspension-feeding benthic infauna.

Food for infauna is also present in the form of benthic macroalgae and sessile epibiota such as sponges and hydroids, especially in and near hard bottom areas. Numerous species of motile carnivores and omnivorous scavengers are adapted to use these food sources. Sampling near dense concentrations of sessile epibiota at hard bottom Station 52 (in the current study area) showed there was a distinct infauna characterized by an unusually large number of syllid polychaete species (e.g., *Haplosyllis spongicola*) (Continental Shelf Associates, Inc. 1987a). Because of the widespread occurrence of live bottom on the shelf, this effect may be significant to the shelf macroinfauna in many areas.

Macroepifauna

Soft bottom areas of the Southwest Florida shelf are inhabited by numerous species of macroepifauna (Environmental Science and Engineering, Inc. et al. 1987). Most large species of motile epifauna on the shelf are sand dwellers that are either restricted to or most abundant on sand, whether or not it is adjacent to rock outcrops or other hard substrate. Typical species on the inner and middle shelf include sea stars (*Astropecten* spp., *Echinaster* spp., *Goniaster tessellatus*, *Luidia* spp., *Narcissia trigonaria*, and *Oreaster reticulatus*); echinoids (*Clypeaster* spp. and *Lytechinus* spp.); holothuroids (*Isostichopus badionotus*); large hermit crabs (*Dardanus* spp., *Paguristes* spp., and *Pagurus* spp.); and conchs (*Strombus* spp.). On the outer shelf, common macroepifauna include crinoids (*Comactinia meridionalis*, *Leptonemaster venustus*, and *Neocomatella pulchellus*), echinoids (*Clypeaster ravenelli*, *Echinolampas depressa*, and *Stylocidaris affinis*), ophiuroids, sea pens, anemones, and others.

Shell hash, rubble, and coralline algal nodules are widespread on the shelf, even in areas of predominantly sand bottom. Species of sponges, stony corals, octocorals, and other sessile epifauna are often visible on the seafloor in these areas (Continental Shelf Associates, Inc. 1987a). Some of these organisms may be attached to hard bottom covered by a sand veneer; others are attached to bits of shell and debris. Also, detached sponges are occasionally seen on the bottom, perhaps dislodged by bottom currents or sediment movement.

There are few quantitative data concerning the abundance or biomass of soft bottom macroepifauna in the study area, other than commercially important shrimp species. Portions of the Tortugas shrimp ground are in the study area and contain high abundances of the pink shrimp *Penaeus duorarum*. Few pink shrimp (or other commercially important species) were collected during the MMS SOFLA study. Aspects of the pink shrimp populations in the study area are discussed by Costello and Allen (1966) and Klima and Costello (1982).

Cluster analyses of trawl data from SOFLA soft bottom stations indicate that species composition of the macroepifauna varies with water depth and substratum type (Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1985). A similar finding was reported by Lyons (1979) for the Hourglass stations north of the study area. In the SOFLA data set, the major break in species composition is at about 40 to 60 m.

Seagrass

The offshore marine seagrass community seen on the West Florida shelf is composed of two *Halophila* species, *H. decipiens* and *H. engelmannii*. *Halophila* species occur seasonally on the West Florida shelf, appearing in late May or early June and disappearing in October or November.

Both *Halophila* species are diminutive when compared with the seagrasses seen in Florida's nearshore waters, bays, and estuaries (**Figure 5.8**). Accordingly, even dense *Halophila* stands never approach the standing crop calculated for climax seagrass species such as *Thalassia* or *Syringodium*. *Halophila decipiens* and *H. engelmannii* are fringing or pioneer species that inhabit the fringes of the climax seagrass beds. They assume regional importance on the West Florida shelf because the gentle slope, clear water, and low wave energy allow them to grow over large areas (Continental Shelf Associates, Inc. and Martel Laboratories, Inc. 1985).

Halophila engelmannii has been reported from a depth of 90 m off the Dry Tortugas (Zieman 1982), but apparently does not occur along the Southwest Florida shelf (Continental Shelf Associates, Inc. 1989). This species is abundant in the deep seagrass meadows north of Tarpon Springs, forming virtually monotypic stands in the 12- to 17-m depth range (Continental Shelf Associates, Inc. and Martel Laboratories, Inc. 1985).

Halophila communities on the West Florida shelf have been the subject of three MMS studies: two in the Florida Big Bend area (Continental Shelf Associates, Inc. and Martel Laboratories, Inc. 1985; Continental Shelf Associates, Inc. 1987b) and one off Southwest Florida (Continental Shelf Associates, Inc. 1989). The latter study includes stations and transects in the study area (**Figure 5.2**). In addition, the effects of exploratory drilling on *Halophila* communities of the Florida Big Bend area were studied by Thompson et al. (1989) during an industry-sponsored monitoring program (see **Chapter 13**).

Distribution. At the peak of its growing season (September), *H. decipiens* is virtually ubiquitous across the Southwest Florida shelf, from a depth of approximately 6 to 27 m (Continental Shelf Associates, Inc. 1989). Total estimated acreage covered by *H. decipiens* on the Southwest Florida shelf during October 1988 was 1.2 million ha (Continental Shelf Associates, Inc. 1989).

The maximum reported depth of occurrence for *H. decipiens* on the Southwest Florida shelf is 37 m, but the species occurs less uniformly in water depths >27 m. *Halophila decipiens* has been reported from a depth of 42 m off St. Croix (Wiginton and McMillan 1979), and *H. engelmannii* has been reported from depths of 90 m off the Dry Tortugas Bank (Zieman 1982). Both *H. decipiens* and *H. engelmannii* grow to depths of at least 25 m in the Florida Big Bend area (Continental Shelf Associates, Inc. and Martel Laboratories, Inc. 1985).

Several algal species grow in association with *H. decipiens*, with *Caulerpa sertularioides* being the most abundant, followed by *C. prolifera* and *C. mexicana*. Off Southwest Florida, a deepwater, thin-bladed phenotype of *C. prolifera* begins to appear at the 24-m contour, becoming more abundant with depth and eventually replacing *H. decipiens* at depths below 37 m (Continental Shelf Associates, Inc. 1989).

Abundance and Biomass. Off Southwest Florida, *H. decipiens* densities range from 0 to 6,500 blades/m^2. The maximum abundance off Southwest Florida is higher than the maximum in the Florida Big Bend area (about 2,000 blades/m^2) (Continental Shelf Associates, Inc. 1989).

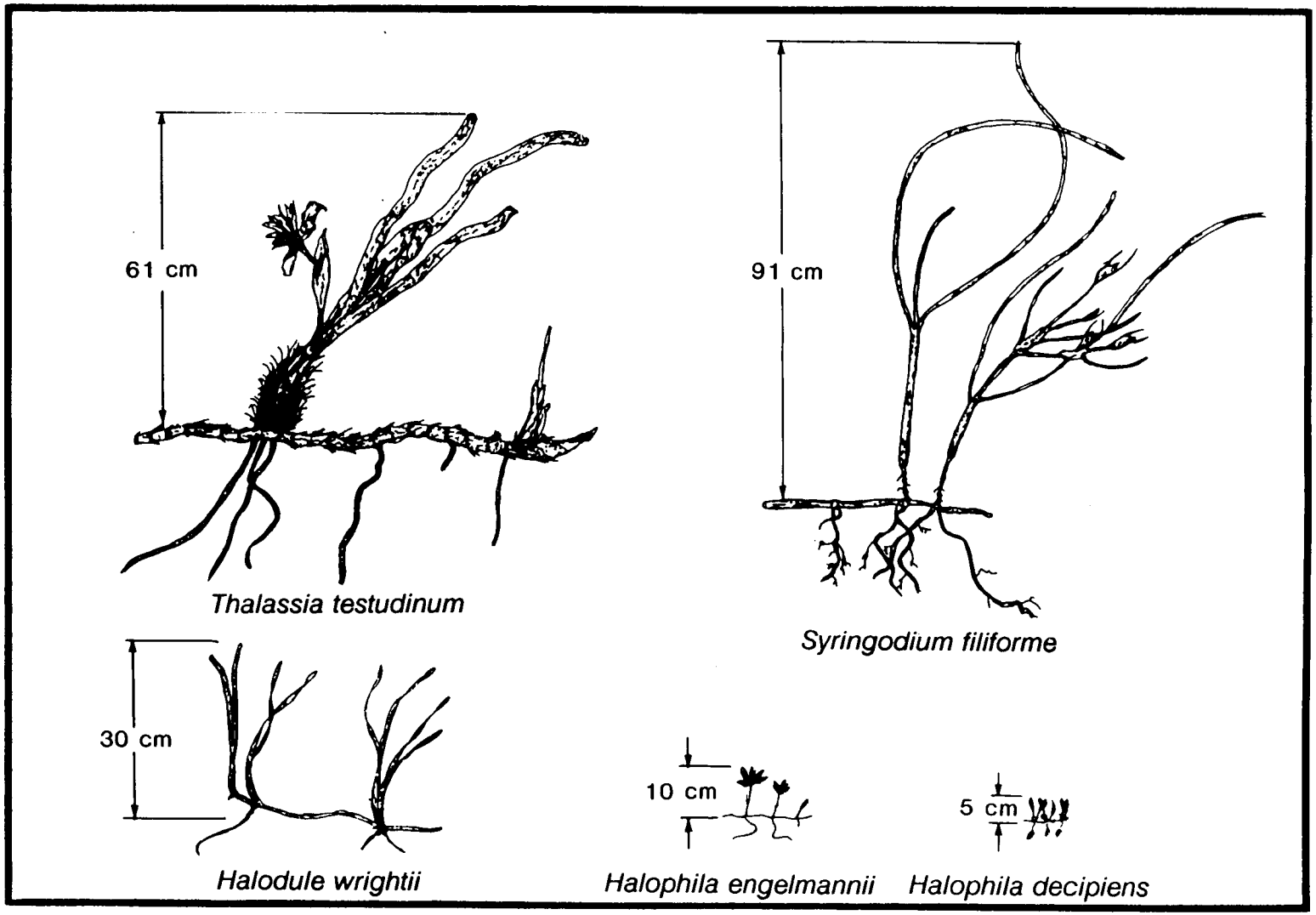

Figure 5.8. Relative sizes of the five species of seagrass seen in South Florida.

Halophila decipiens grows most densely in areas of firmly packed sand and silty sand. This species grows sparsely in areas of coarser substrate and is not abundant in hard bottom areas (usually covered by a thin sand veneer). In these areas, macroalgal species make a higher contribution to the observed floral density.

The mean above-ground biomass for *H. decipiens* at Southwest Florida shelf stations sampled in 1988 was 194 mg/m^2. This compares with a biomass of 161 mg/m^2 calculated for similar seagrass meadows in the Florida Big Bend area (Continental Shelf Associates, Inc. 1987b).

The biomass of *H. decipiens* is hundreds to thousands of times lower than the biomass of seagrass in the climax, nearshore seagrass beds. The dry-weight biomass figures provided by Zieman (1982) for the three nearshore seagrass species growing on Florida's southwest coast can be compared with the data for *H. decipiens*, as follows:

Halodule wrightii	50	to	250 g/m^2
Syringodium filiforme	100	to	300 g/m^2
Thalassia testudinum	500	to	3,100 g/m^2
Halophila decipiens	0.002	to	1 g/m^2

Seasonality. The growing season for *H. decipiens* on the Southwest Florida shelf extends from late May or early June through early October (Continental Shelf Associates, Inc. 1989). Biomass increases rapidly throughout June and July, begins to level off in August, and peaks in September. New blades appear and older blades increase in length throughout June, July, August, and September, but as the September growing season climax approaches, fewer new leaves appear.

Flowering has not been observed in the *H. decipiens* meadows off Southwest Florida. In the Florida Big Bend area, *H. decipiens* flowering was observed in late August/early September 1985 (Continental Shelf Associates, Inc. 1988b). Flowering was also reported in late August and early September of 1986 and 1987 for *H. decipiens* off Anclote Key, on the West Florida coast just north of Tarpon Springs (Dawes et al. 1989). We assume that *H. decipiens* on the Southwest Florida shelf flowers in late August and early September; this event probably was missed during the MMS study in this area because of the timing of the sampling efforts.

The growing season for *H. decipiens* off West Florida probably begins in late May and early June (Continental Shelf Associates, Inc. 1989). Apparently, the peak of the growing season for all seagrass species along this coastline occurs in late August and September (Zieman 1982; Iverson and Bittaker 1986; Dawes et al. 1989).

The end of the *H. decipiens* growing season probably varies from year to year depending on the weather. New growth tapers off in September, but the existing plants may persist for several months into late fall and early winter. Off Southwest Florida, low densities of *H. decipiens* were seen in late November 1988, but the species had disappeared by early January 1989 (Continental Shelf Associates, Inc. 1989). During the previous growing season, the seagrass disappeared between August and November, following the passage of a hurricane and a major tropical depression near the area. Off Anclote Key (north of Tampa Bay), Dawes et al. (1989) reported that *H. decipiens* occurs from July through September. Both *H. decipiens* and *H. engelmannii* were seen in the Big Bend area during February 1985 (Continental Shelf Associates, Inc. and Martel Laboratories, Inc. 1985).

Environmental Influences. *Halophila decipiens* growth is limited by light, salinity, and temperature (Trocine et al. 1982; Zieman 1982; Dawes et al. 1989). It is a stenohaline

species and shows a strong photoinhibitory response at light levels above 300 $\mu E/m^2/s$. Its most efficient photosynthetic response is at lower irradiance levels (Dawes et al. 1989). Off Southwest Florida, this species reaches its maximum density in depths between 21 and 27 m, but this pattern may reflect the availability of suitable substrate, rather than a relationship to light or other parameters. Between the 21- and 27-m depth contours, there is a more or less continuous band of wave-sorted, fine sand ribbons that form ideal *H. decipiens* habitat. Closer to shore, there are large areas of hard bottom covered by a thin sand veneer, which is not as suitable for *Halophila* growth. Beyond 27 m, sediments become coarser and show a greater concentration of algal rubble. Fine, well-packed sand occurs in depths beyond approximately 33.5 m, but *H. decipiens* does not reach the densities seen in the 21- to 27-m depth range. *Halophila decipiens* apparently does not grow beyond a depth of 37 m in the study area, even where suitable substrate is present.

Light, temperature, and wave action determine how long *H. decipiens* persists into the winter months after the growing season has peaked. As the waters off West Florida turn cooler and the days grow shorter in late fall and early winter, the *H. decipiens* meadows begin to deteriorate. New growth, in the form of new blades, declines dramatically in October. The older leaves and root systems also begin to deteriorate about this time. There is an increased incidence of blanching, or loss of chlorophyll from leaves still attached to the rhizome system, and the rhizomes themselves appear to begin to break up, becoming less firmly rooted in the substrate. Protein, lipid, and soluble carbohydrate ratios within the plant tissue may begin to shift as the growth season ends. In their weakened, post-growth climax phase, the offshore *H. decipiens* seagrass meadows are easily uprooted and washed away by wave action and currents.

Although no definitive studies have been done, it seems reasonable to consider light levels as one of the prime mechanisms triggering seed germination, flowering, and cessation of new shoot production in *H. decipiens*.

Ecological Importance. Seagrass biomass in *Thalassia* and *Syringodium* beds is significantly correlated with invertebrate species diversity and abundance, but this correlation is thought to result from the seagrass beds' structural complexity rather than their primary productivity. These beds represent a haven from predators rather than a food source for its residents (Heck and Wetstone 1977; Coles et al. 1987).

Halophila seagrass meadows do not provide the kind of habitat structure that exists in nearshore seagrass beds. Accordingly, within *Halophila* seagrass meadows, the associated faunal species and densities have been shown to be similar to neighboring areas of non-vegetated bottom (den Hartog 1977).

Few marine organisms feed on seagrasses directly. The detrital food web is the primary pathway of trophic energy transfer from seagrass beds (Zieman 1982). This pattern seems to hold for *H. decipiens*; Dirnberger and Kitting (1988) reported that only 2% of *H. decipiens* blades collected off St. Croix showed signs of herbivore grazing. They suggested that herbivores feed infrequently on *H. decipiens* because of sulphated phenolic acids reported in this species by McMillan et al. (1980).

CONCLUSIONS

The two continental shelf environments in the study area--the Southwest Florida shelf and the Straits of Florida shelf--have many benthic organisms and some benthic communities in common, but the distribution of habitats is distinctly different. The Southwest Florida shelf is broad (up to 300 km [162 nmi] wide), and for the most part, hard bottom habitats are scattered apparently at random across the shelf, probably

reflecting irregularities in the underlying rock. The exceptions are along two north-south oriented, partly buried, ancient reef features (Pulley Ridge and Howell Hook), which support distinctive hard bottom communities. In contrast, the Straits of Florida shelf is narrow (a few kilometers wide), and hard bottom habitat consists of a deep reef and associated coralline rubble zone that is presumed to extend in a narrow band parallel to the Florida Reef Tract.

The presence of hard bottom habitats and seagrass meadows on the continental shelf is important because these areas are considered live bottom, and are therefore accorded special protection under a stipulation attached to all leases in the eastern Gulf of Mexico (MMS 1987). This type of stipulation, which presumably would be applied to any leases in the study area, requires a visual survey of the seafloor within 1,000 m of any proposed activity site in a water depth of 100 m or less. Based on the results of the survey, the MMS can choose to protect live bottom by requiring relocation of drilling operations, or shunting or onshore disposal of drilling fluids and cuttings. Biological monitoring can also be required.

The current live bottom stipulation is based on a conception of live bottom areas as rare, valuable, and sensitive "oases" in a "desert" of sand bottom. This conception is simplistic in several respects:

- Terminology. The term "live bottom" is unfortunate, because it implies that everything else is "dead bottom." Danek and Lewbel (1986) question the use of the term to categorize portions of the shelf, maintaining that the shelf is essentially a mosaic of substratum and community types. Their view is reasonable for many areas of the shelf where habitat distribution is patchy on several spatial scales. Also, because many organisms move between habitats (such as fishes that use hard bottom areas for shelter and soft bottom areas for foraging), a lease stipulation that focuses on hard bottom areas and sessile epifauna ignores the complex spatial mosaic of benthic communities and the possible interactions among habitats.

- Rarity. Live bottom areas are common, not rare, on the West Florida shelf. Parker et al. (1983) estimated that 38% of the seafloor between Key West and Pensacola consists of "reef habitat." Similarly, Phillips et al. (1990b) estimated that live bottom (excluding seagrass meadows) accounts for 31% of the Southwest Florida shelf. Even areas categorized as soft bottom in the SOFLA study support sparse populations of sessile epifauna attached to bits of rubble and debris. Truly rare are those areas characterized by high-relief outcrops, very dense epifaunal or macroalgal growth, and/or populations of reef-building corals (e.g., *Agaricia* deep reef).

- Value/Productivity. Although some live bottom areas support a high *biomass* of sessile epifauna, there are no data comparing the *productivity* of these areas with that of the surrounding sand bottom. Live bottom areas are often considered important because they provide habitat for fishes, but much of the food to sustain fish populations may come from the surrounding soft bottom, which provides foraging grounds for species that feed on macroinfauna. From a commercial fisheries standpoint, the most valuable areas on the Southwest Florida shelf are the Tortugas and Sanibel shrimp grounds, which are soft bottom areas.

- Sensitivity to Environmental Disturbance. Sessile species are often considered sensitive to sedimentation because they cannot evade burial. However, many species of stony corals, octocorals, and sponges present on the Southwest Florida shelf must tolerate sedimentation and scour in order to survive, because sediment movement is a significant natural phenomenon in the area (Danek and Lewbel 1986). Conversely, many species of macroinfauna and soft bottom macroepifauna might be affected by subtle changes in sediment texture due to deposition of drilling fluids and cuttings. The point is not that sessile organisms are tolerant to drilling discharges, but rather that greater sensitivity should not be assumed *a priori* (National Research Council 1983).

- Importance of Deepwater Seagrass Meadows. The ecological significance of nearshore seagrass beds is well established (**Chapter 4**). This significance derives from the structuring influence of nearshore seagrasses (especially *Thalassia*) on their environment. In contrast, the deepwater seagrass *Halophila* is diminutive, and its blade density and biomass on the continental shelf are hundreds or thousands of times lower than that of *Thalassia* in Florida Bay seagrass beds. There is no evidence that this species structures the environment any more than the macroalgae that grow more widely across the shelf. If *Halophila* meadows are to be protected, why not also protect comparably dense areas of macroalgal growth? Conversely, if macroalgal populations are not to be protected, why protect *Halophila*?

Ideally, a management framework for protection of offshore benthic habitats should be based on data concerning their *rarity*, *value* (aesthetic, ecological, economic), and *sensitivity* (to sedimentation, mechanical disturbance, etc.). These attributes should not simply be assumed to result from the presence of sessile epifauna or seagrass. The amount of information available to serve as a basis for management differs for each topic:

- Rarity. Considerable information is available concerning the commonness or rarity of particular community types on the Southwest Florida shelf, but little is known concerning the distribution of benthic habitats on the shelf offshore of the Florida Reef Tract. Systematic geophysical and visual surveys of this area will be needed if leasing occurs there.

- Value. There is not enough information to categorize South Florida offshore habitats by ecological and economic value. To determine ecological and economic value of offshore communities, more information is needed concerning trophic relationships and ecosystem processes. Benthic productivity needs to be measured, and links to existing or potential fishery species need to be studied.

- Sensitivity. Little is known of the sensitivity of South Florida benthic communities to habitat disruption and sedimentation, which are two possible consequences of offshore oil and gas activities. Colonization plates were deployed during the SOFLA study, but these provided no information about how defaunated areas of the seafloor might be recolonized. Field experiments could be designed to address this problem. In addition, if further drilling is conducted elsewhere on the Southwest Florida shelf, quantitative monitoring of biological effects would provide useful data for evaluating protective measures in the study area.

Because effects of drilling activities are typically local (e.g., within a few hundred meters of a drill site--see **Chapter 13**), protection of rare habitats and communities should be the first priority. Other areas may be more valuable or sensitive, but if they

are widespread, it is not as critical to lose a small percentage of the total. The information on habitat distribution (Southwest Florida shelf) provides a good starting point for categorizing prospective drill sites according to the rarity or commonness of the benthic community. Additional information about the value and sensitivity of benthic communities in the study area would provide a better basis for management decisions.

The middle and outer portions of the Southwest Florida shelf within the study area support unusual benthic communities, including the deep *Agaricia* reef and other areas of lush algal growth. These are the kinds of communities most likely to be accorded special protection in the context of oil and gas operations, yet little is known of their spatial extent or basic ecology. Additional research is needed to determine the role of environmental factors, especially light and nutrients, in the development of these communities.

REFERENCES CITED

Agassiz, A. 1888. *Three cruises of the United States Coast and Geodetic Survey steamer "Blake" in the Gulf of Mexico, in the Caribbean Sea, and along the Atlantic coast of the United States from 1877 to 1880.* Cambridge, MA: Houghton, Mifflin and Co., Riverside Press.

Antonius, A. 1974. *Final report of the coral reef group of the Florida Keys project for the project year 1973.* Harbor Branch Foundation Tech. Rep. Ft. Pierce.

Bishof, D. E. 1980. The ecology of molluscan infauna on the southwestern continental shelf of Florida. M.S. thesis, Univ. of South Florida.

Blake, N. J. 1979. Infaunal macromolluscs of the eastern Gulf of Mexico. In *The Mississippi, Alabama, Florida outer continental shelf baseline environmental survey 1977/1978*, Ch. 14. Washington, DC: U.S. Department of the Interior, Bureau of Land Management.

Boesch, D. F. 1979. Benthic ecological studies. In *Middle Atlantic outer continental shelf environmental studies, Vol. II-B, Chemical and biological benchmark studies*, ed. E. M. Burreson, D. F. Boesch, and B. L. Laird, Ch. 6. Washington, DC: U.S. Department of the Interior, Bureau of Land Management.

Bohnsack, J. A. 1983. Resiliency of reef fish communities in the Florida Keys following a January 1977 hypothermal fish kill. *Environ. Biol. Fish.* 9:41-53.

Bosellini, A., and R. N. Ginsburg. 1971. Form and internal structure of Recent algal nodules (rhodolites) from Bermuda. *J. Geol.* 79: 669-682.

Bright, T. J. 1981. A brief comparison of the reef system off Key Largo, Florida with the Flower Garden reef system, northwestern Gulf of Mexico. In *Key Largo Coral Reef National Marine Sanctuary Deep Water Resource Survey*, ed. S. C. Jameson, 69-74. NOAA Tech. Rep. CZ/SP-1. Washington, DC.

Bullock, L. H., and G. B. Smith. 1979. Impact of winter cold fronts upon shallow water reef communities off west-central Florida. *Fla. Sci.* 42:169-172.

Cairns, S. D. 1977. Stony corals. I. Caryophylliina and Dendrophylliina (Anthozoa: Scleractinia). *Memoirs of the Hourglass Cruises, Vol. III, Pt. IV.* St. Petersburg: Florida Department of Natural Resources, Marine Research Laboratory.

Cairns, S. D. 1978. A checklist of the ahermatypic Scleractinia of the Gulf of Mexico, with the description of a new species. *Gulf Res. Rep.* 6:9-15.

Coles, R. G., W. J. Lee Long, B. A. Squire, and J. M. Bibby. 1987. Distribution of seagrasses and associated juvenile commercial penaeid prawns in north-eastern Queensland waters. *Aust. J. Mar. Freshwat. Res.* 103-119.

Continental Shelf Associates, Inc. 1985. *Southwest Florida shelf regional biological communities survey, marine habitat atlas.* New Orleans: U.S. Department of the Interior, Minerals Management Service.

Continental Shelf Associates, Inc. 1987a. *Southwest Florida shelf regional biological communities survey. Year 3 final report.* OCS Study MMS 86-0109. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Continental Shelf Associates, Inc. 1987b. *Assessment of hurricane damage in the Florida Big Bend seagrass beds.* OCS Study MMS 87-0001. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Continental Shelf Associates, Inc. 1988a. *Photodocumentation survey of Pulley Ridge Area Block 799, eastern Gulf of Mexico.* Report prepared for Mobil Exploration & Producing U.S., Inc. New Orleans.

Continental Shelf Associates, Inc. 1988b. *Monitoring of drillsite A in the Gainesville area OCS block 707.* Report prepared for Sohio Petroleum Company. Lafayette, LA.

Continental Shelf Associates, Inc. 1989. *Southwest Florida nearshore benthic habitat study.* OCS Study MMS 89-0080. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Continental Shelf Associates, Inc. 1990. *Videodocumentation of three ordnance sites west of Key West, Florida.* Report prepared for Water and Air Research, Inc. Gainesville, FL.

Continental Shelf Associates, Inc. and Martel Laboratories, Inc. 1985. *Florida Big Bend seagrass habitat study, narrative report.* New Orleans: U.S. Department of the Interior, Minerals Management Service.

Costello, T. J., and D. M. Allen. 1966. Migrations and geographic distribution of pink shrimp, *Penaeus duorarum*, of the Tortugas and Sanibel grounds, Florida. *Fish. Bull.* 65(2):449-459.

Cummins, R., Jr., J. B. Rivers, and P. Struhsaker. 1962. Snapper trawling explorations along the southeastern coast of the United States. *Commer. Fish. Rev.* 24:1-7.

Dames & Moore. 1979. *The Mississippi, Alabama, Florida outer continental shelf baseline environmental survey, MAFLA 1977/1978. Vol. I-A, Program synthesis report.* Washington, DC: U.S. Department of the Interior, Bureau of Land Management. Available through NTIS, Order No. PB-294-277/AS.

Danek, L. J., and G. S. Lewbel, ed. 1986. *Southwest Florida shelf benthic communities study. Year 5 final report.* OCS Study MMS 86-0076. New Orleans: U.S. Department of the Interior, Minerals Management Service.
Darcy, G. H., and E. J. Gutherz. 1984. Abundance of demersal fishes on the West Florida shelf, January 1978. *Bull. Mar. Sci.* 34:81-105.
Dawes, C. J., C. S. Lobban, and D. A. Tomasko. 1989. A comparison of the physiological ecology of the seagrasses *Halophila decipiens* Ostenfeld and *H. johnsonii* Eiseman from Florida. *Aquat. Bot.* 33:149-154.
den Hartog, C. 1977. Structure, function, and classification in seagrass communities. In *Seagrass ecosystems: A scientific perspective*, ed. C. P. McRoy and C. Helfferich, 89-121. New York: Marcel Dekker.
Devany, T. 1969. Ecological interpretation of distribution of the lanternfishes (Myctophidae) in the Straits of Florida. Ph.D. diss., Univ. of Miami.
Dirnberger, J. M., and C. L. Kitting. 1988. Browsing injuries to blades of *Halophila decipiens* within a deep seagrass meadow. *Aquat. Bot.* 29:373-379.
Environmental Science and Engineering, Inc., LGL Ecological Research Associates, Inc., and Continental Shelf Associates, Inc. 1987. *Southwest Florida shelf ecosystems study data synthesis.* OCS Study MMS 87-0023. New Orleans: U.S. Department of the Interior, Minerals Management Service.
Galtsoff, P. S. 1954. Historical sketch of the explorations in the Gulf of Mexico. In *Gulf of Mexico. Its origin, waters, and marine life*, ed. P. S. Galtsoff, 3-36. Washington, DC: U.S. Government Printing Office.
Ginsburg, R. N., and N. P. James. 1974. Holocene carbonate sediments of continental shelves. In *Geology of continental margins*, ed. C. A. Burk and C. L. Drake, 137-156. New York: Springer-Verlag.
Goldberg, W. M. 1970. Some aspects of the ecology of the reefs off Palm Beach County, Florida, with emphasis on the Gorgonacea and their bathymetric distribution. M.S. thesis, Florida Atlantic Univ.
Goldberg, W. M. 1973. The ecology of the coral-octocoral communities off the Southeast Florida coast: Geomorphology, species composition, and zonation. *Bull. Mar. Sci.* 23:465-488.
Hanson, R. B., K. R. Tenore, S. Bishop, C. Chamberlain, M. M. Pamatmat, and J. Tietjen. 1981. Benthic enrichment in the Georgia Bight related to Gulf Stream intrusions and estuarine outwelling. *J. Mar. Res.* 39:417-441.
Heard, R. W. 1979. Macroinfaunal crustaceans. In *The Mississippi, Alabama, Florida outer continental shelf baseline environmental survey 1977/1978*, Ch. 16. Washington, DC: U.S. Department of the Interior, Bureau of Land Management.
Heck, K. L., Jr., and G. S. Wetstone. 1977. Habitat complexity and invertebrate species richness and abundance in tropical seagrass meadows. *J. Biogeogr.* 4:1135-1142.
Holmes, C. W. 1981. *Late Neocene and Quaternary geology of the southwestern Florida shelf and slope.* U.S. Department of the Interior Geological Survey, Open File Rep. No. 81-1029.
Holmes, C. W. 1985. Accretion of the South Florida platform, late Quaternary development. *Am. Assoc. Pet. Geol. Bull.* 69:149-160.
Hopkins, T. 1979. Macroepifauna. In *The Mississippi, Alabama, Florida outer continental shelf baseline environmental survey, 1977/1978*, 789-835. Washington, DC: U.S. Department of the Interior, Bureau of Land Management.
Hubbard, J. A. E. B., and Y. B. Pocock. 1972. Sediment rejection by Recent scleractinian corals: A key to palaeo-environmental reconstruction. *Geol. Rundsch.* 61:598-626.
Iverson, R. L., and H. F. Bittaker. 1986. Seagrass distribution and abundance in eastern Gulf of Mexico coastal waters. *Estuar. Coast. Shelf Sci.* 22(5):577-602.
Jaap, W. C. 1984. *The ecology of the South Florida coral reefs: A community profile.* FWS/OBS-82/08. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.
Jameson, S. C. 1981. Biological zonation. In *Key Largo Coral Reef National Marine Sanctuary Deep Water Resource Survey*, ed. S. C. Jameson, 1-5. NOAA Tech. Rep. CZ/SP-1. Washington, DC.
Jordan, G. F., and H. B. Stewart, Jr. 1959. Continental shelf off Southwest Florida. *Am. Assoc. Pet. Geol. Bull.* 43: 974-991.
Joyce, E. A., Jr., and J. Williams. 1969. Rationale and pertinent data. *Memoirs of the Hourglass Cruises, Vol. I, Pt. I.* St. Petersburg: Florida Department of Natural Resources, Marine Research Laboratory.
Klima, E. F., and T. J. Costello. 1982. *The Tortugas sanctuary study, May 1981-February 1982.* NOAA Tech. Mem. No. NMFS-SEFC-104. Washington, DC: U.S. Department of Commerce.
Lasker, H. R. 1981. A comparison of the particulate feeding abilities of three species of gorgonian soft coral. *Mar. Ecol. Prog. Ser.* 5:61-67.
Lyons, W. G. 1979. Molluscan communities of the West Florida shelf. *Trans. Am. Malacol. U.* 1979:37-40.
Marine Resources Research Institute. 1984. *South Atlantic OCS Area Living Marine Resources Study, Phase III.* Washington, DC: U.S. Department of the Interior, Minerals Management Service.
McMaster, R. L., and J. T. Conover. 1966. Recent algal stromatolites from the Canary Islands. *J. Geol.* 74:647-652.
McMillan, C., O. Zapata, and L. Escobar. 1980. Sulphated phenolic compounds in seagrasses. *Aquat. Bot.* 8:267-278.
Minerals Management Service. 1987. *Final environmental impact statement, proposed oil and gas lease sales 113/115/116, Gulf of Mexico OCS region.* OCS EIS MMS 87-0077. New Orleans.
National Oceanic and Atmospheric Administration. 1980. Final environmental impact statement, proposed Looe Key National Marine Sanctuary. Washington, DC.
National Research Council. 1983. *Drilling discharges in the marine environment.* Washington, DC: National Academy Press.
Parker, R. O., Jr., D. R. Colby, and T. D. Willis. 1983. Estimated amount of reef habitat on a portion of the U.S. South Atlantic and Gulf of Mexico continental shelf. *Bull. Mar. Sci.* 33:935-940.
Phillips, N. W., D. A. Gettleson, and K. D. Spring. 1990a. Benthic biological studies of the Southwest Florida shelf. *Am. Zool.* 30:65-75.
Phillips, N. W., K. D. Spring, and D. A. Gettleson. 1990b. A visual survey of benthic habitats of the Southwest Florida shelf. Unpubl. manuscript.
Rabalais, N. N., and D. F. Boesch. 1987. Dominant features and processes of continental shelf environments of the United States. In *Long-term environmental effects of offshore oil and gas development*, ed. D. F. Boesch and N. N. Rabalais, 71-147. New York: Elsevier Applied Science.
Rice, S. A. 1984. *Effects of suspended sediment and burial upon survival and growth of eastern Gulf of Mexico reef corals.* Report by Mote Marine Laboratory to the U.S. Environmental Protection Agency. Sarasota.

Ricklefs, R. E. 1979. *Ecology*, 2nd Ed. New York: Chiron Press.
Robins, C. H. 1968. The comparative osteology and ecology of the synaphobranchid eels of the Straits of Florida. Ph.D. diss., Univ. of Miami.
Schmahl, G. P. 1984. Sponges. In *The ecology of the South Florida coral reefs: A community profile*, ed. W. C. Jaap, 37-40. FWS/OBS-82/08. Washington, DC: U.S. Fish and Wildlife Service.
Schumacher, H., and H. Zibrowius. 1985. What is hermatypic? A redefinition of ecological groups in corals and other organisms. *Coral Reefs* 4:1-9.
Shinn, E. A. 1981. Geology. In *Key Largo Coral Reef National Marine Sanctuary Deep Water Resource Survey*, ed. S. C. Jameson, 59-64. NOAA Tech. Rep. CZ/SP-1. Washington, DC.
Smith, G. B. 1976. *Ecology and distribution of eastern Gulf of Mexico reef fishes*. Florida Marine Research Publ. No. 19. St. Petersburg: Florida Department of Natural Resources, Marine Research Laboratory.
Staiger, J. C. 1970. The distribution of benthic fishes found below two hundred meters in the Straits of Florida. Ph.D. diss., Univ. of Miami.
Starck, W. A. II. 1968. A list of fishes of Alligator Reef, Florida, with comments on the nature of the Florida reef fish fauna. *Undersea Biol.* 1:4-40.
Struhsaker, P. 1969. Demersal fish resources: composition, distribution, and commercial potential of the continental shelf stocks off southeastern United States. *Fish. Ind. Res.* 4:261-300.
Tenore, K. R. 1979. Macroinfaunal benthos of South Atlantic/Georgia Bight. In *South Atlantic benchmark program, outer continental shelf (OCS) environmental studies, Vol. 3*. Washington, DC: U.S. Department of the Interior, Bureau of Land Management.
Thompson, M. J., A. D. Hart, and C. W. Kerlin. 1989. Exposure of deep seagrass beds off the west coast of Florida to discharged drilling effluents. In *Drilling wastes. Proceedings of the 1988 International Conference on Drilling Waste*, ed. F. R. Engelhardt, J. P. Ray, and A. H. Gillam, 137-156. London: Elsevier.
Trocine, B. P., J. D. Rice, and G. N. Wells. 1982. Photosynthetic response of seagrasses to UV-A radiation and the influence of visible light intensity. *Plant Physiol.* 69:341-344.
Vittor, B. A. 1979. Macroinfaunal polychaetes. In *The Mississippi, Alabama, Florida outer continental shelf baseline environmental survey 1977/1978*, Ch. 15. Washington, DC: U.S. Department of the Interior, Bureau of Land Management.
Walton Smith, F. G. 1954. Biology of the commercial sponges. In *Gulf of Mexico: Its origin, waters, and marine life*, ed. P. S. Galtsoff, 263-266. Washington, DC: U.S. Government Printing Office.
Wenner, E. L., D. M. Knott, R. F. Van Dolah, and V. G. Burrell, Jr. 1983. Invertebrate communities associated with hard bottom habitats in the South Atlantic Bight. *Estuar. Coast. Shelf Sci.* 17:143-158.
Wiginton, J. R., and C. McMillan. 1979. Chlorophyll composition under controlled light conditions as related to the distribution of seagrasses in Texas and the U.S. Virgin Islands. *Aquat. Bot.* 6:171-184.
Wilkinson, C.R. 1987. Interocean differences in size and nutrition of coral reef sponge populations. *Science* 236:1654-1657.
Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1983. *Southwest Florida shelf ecosystems study, marine habitat atlas*. New Orleans: U.S. Department of the Interior, Minerals Management Service. Vol. 2 available through NTIS, Order No. PB84-113315.
Woodward-Clyde Consultants and Continental Shelf Associates, Inc. 1985. *Southwest Florida shelf ecosystems study--Year 2*. New Orleans: U.S. Department of the Interior, Minerals Management Service.
Woodward-Clyde Consultants and Skidaway Institute of Oceanography. 1983. *Southwest Florida shelf ecosystems study--Year 2 modification*. New Orleans: U.S. Department of the Interior, Minerals Management Service.
Zieman, J. C. 1982. *The ecology of seagrasses of South Florida: A community profile*. FWS/OBS-82/25. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

CHAPTER 6
PLANKTON

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(Phytoplankton)

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(Zooplankton and Ichthyoplankton)

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INTRODUCTION

Water column studies, particularly studies of plankton dynamics, have traditionally not been included in investigations of environmental effects of oil and gas exploration and development. A commonly held view is that any effects that occur in open water will be short-lived because current transport will disperse the pollutant and re-inoculate the area with a similar community. However, this is an overly simplistic view, for several reasons. Subtropical and tropical, oligotrophic waters such as those of the Gulf

of Mexico and Straits of Florida have tightly coupled pelagic food webs. Steady-state phytoplankton biomass and productivity are maintained by zooplankton grazing and nutrient excretion ("regenerated productivity" *sensu* Dugdale and Goering 1967). Thus, these ecosystems may be extremely vulnerable to perturbations at lower trophic levels. Also, larvae of several commercially important fishery species have pelagic eggs that undergo initial development in surface waters, where they are particularly vulnerable to surface disturbance (e.g., oil spills). Because of the restricted nature of seasonal spawning and the concentration of eggs and larvae over spawning grounds and within nursery areas, nearshore and estuarine species are probably far more vulnerable to damage from human activities than are the open ocean species. More developed pre-flexion larvae and especially flexion larvae of many estuarine species descend to near-bottom waters and so are vulnerable to bottom disturbances. Because fish larvae have much longer generation times than most zooplankton and phytoplankton species, they have a reduced capacity for rapid recovery from environmental disturbance.

An adequate data base on plankton community structure and dynamics is necessary to predict the environmental consequences of any human activity in the study area. Three sections of this chapter summarize information on phytoplankton, zooplankton, and ichthyoplankton in the South Florida area. A brief overview of hydrography is presented first.

HYDROGRAPHIC CONDITIONS

Thomas L. Hopkins

In order to understand plankton dynamics in the study area, the hydrographic conditions must be briefly considered. The study area can be divided into three different biological provinces: (1) oceanic waters deeper than 200 m; (2) shelf waters (<200 m); and (3) nearshore waters, including Florida Bay and the Florida Keys and Reef Tract.

Oceanic Waters

Deep oceanic waters, particularly in the area of concern, are dominated by the Loop Current. This current originates in the Straits of Yucatan and arcs anti-cyclonically through the eastern Gulf of Mexico to exit through the Straits of Florida, where it is known as the Florida Current. This rapid current has a quasi-annual cycle of maximum penetration into the Gulf during spring and summer, followed by decay in fall and winter (Leipper 1970; Maul 1977). The main axis of the Loop Current generally stays offshore of the shelf break (183 m depth), meandering through the Straits of Florida about 80 km (43 nmi) south of Key West, and turning northward to pass about 20 km (11 nmi) east of Miami (Brooks and Niiler 1975) (see **Chapter 2**). Deep counter-currents have been found about 20 km (11 nmi) south of Key West (Lee et al. 1977) as well as off Miami (Duing 1975).

Shelf Waters

Loop Current intrusions and tides dominate Southwest Florida shelf waters (Mitchum and Sturges 1982). However, Loop Current-generated circulation patterns on the shelf tend to be less important during winter when the current is slowest (Austin and Jones 1974). Loop Current water mixes with eastern Gulf water to form water with intermediate temperature and salinity characteristics (Transition Water) which meanders on and off the shelf (Leipper 1970). The depth of the year-round mixing zone (thermo-cline) in Transition Water averages 25 to 50 m (Lancraft et al. 1988; Lancraft et al. unpubl. hydrographic data).

Cold core (upwelling) cyclonic rings are generated by the Loop Current on the Southwest Florida shelf north of Florida Bay (Chew 1955; Paluszkiewicz et al. 1983) and have also been found south of the Keys on the Pourtales Terrace (Niiler and Richardson 1973; Chew 1974) and in the Straits of Florida (Lee and Atkinson 1983). These rings serve to transport plankton both landward and longshore (northward). They are particularly important in carrying larval pink shrimp (*Penaeus duorarum*) from their breeding grounds near the Dry Tortugas to their postlarval nursery areas in embayments south of the Everglades (Rehrer et al. 1967). They may also be responsible for the enhanced biological productivity associated with the Southwest Florida shelf (Chew 1955; Khromov 1965; Bogdanov et al. 1968; Austin and Jones 1974).

Seasonal results of a drift bottle survey on the shelf north of the study area indicate a persistent wintertime southward flow. However, spring and summer releases each indicated both southward and northward flows (Williams et al. 1977). This scatter was interpreted as a result of the Loop Current shelf intrusions and eddies disrupting the typical southward flow entrained by the Loop Current.

Tides tend to dominate the shallow areas of the shelf as indicated by near-bottom current meter data (Danek and Lewbel 1986). Data from a station 50 km (27 nmi) west of Cape Sable and another 10 to 20 km (5 to 11 nmi) north of the Dry Tortugas indicate relatively rapid east-west and north-south tidal flow, respectively. These currents were recorded along with a consistent (all seasons) slow southward flow forced by the Loop Current.

Nearshore Waters

Hydrographic conditions of nearshore waters, including Florida Bay, are primarily determined by freshwater runoff and rainfall (Schomer and Drew 1982). They are variably modified by tidal flux and longshore currents and therefore experience wide variability in salinities (13 to 52 ppt) and temperatures (15 to 38 °C) (Schomer and Drew 1982). Hypersalinity often occurs during the dry season (Tabb et al. 1962), especially in the cluster of marine basins north of the upper Florida Keys.

In the Florida Keys, nearshore hydrographic conditions are different from estuarine conditions. Near coral reefs, oceanic currents and associated cyclonic eddies become more important, and therefore salinities and temperatures approach ocean conditions (Schomer and Drew 1982).

PHYTOPLANKTON

Gabriel A. Vargo

Introduction

Extensive data are not available for phytoplankton in the study area. Much of the information comes from studies conducted 10 to 20 years ago. The variety of methods used by the various investigators makes intercomparison of their results difficult. Developments in methodology since that period could alter our perceptions of community dynamics. The few recent studies tend to confirm earlier results which indicated that (1) diatoms, particularly *Skeletonema costatum*, are the dominant taxa in nearshore waters; (2) dinoflagellate populations during non-red-tide blooms are a minor component of the phytoplankton community; and (3) population abundance varies considerably throughout the year. However, recent work is also limited in scope, particularly with respect to a lack of seasonal data. Several aspects of the available data have been emphasized for their potential ecological significance, along with recommendations for additional research.

Community Composition

Gulf of Mexico

Nearshore Waters. Information on phytoplankton community composition for nearshore locations in the study area is limited. Steidinger et al. (1967) and Saunders et al. (1967) compiled species lists, the temperature and salinity range for each species, and the seasonal abundance of dinoflagellates and diatoms for 19 stations along the west coast of Florida. Data from stations located on Big Carlos Pass (Estero Bay), Caxambas Pass (Marco Island), and Stump Pass (Lemon Bay) would be pertinent. Steidinger et al. (1967) emphasized the difficulty in determining species and community dynamics due to the frequency of sampling. Their comparison of cell counts in water samples collected at weekly and monthly intervals indicated that (1) weekly fluctuations in genera were not seen in monthly samples; (2) monthly samples displayed a smooth gradation in abundance, whereas weekly samples showed a high degree of variability in abundance throughout the month; and (3) not all species were found in weekly compared with monthly samples. Descriptions of seasonal cycles of major species and community analysis would therefore be questionable. Common dinoflagellate species in these estuarine areas included *Ceratium furca* and *C. hircus*, *Gonyaulax balechii*, *Gymnodinium splendens*, and several *Peridinium* and *Prorocentrum* species. *Ptychodiscus brevis*, the Gulf toxic red tide organism, dominated during blooms. Population abundance varied widely; for example, at Caxambas Pass the seasonal range was 0 to 14,000 cells/L while at Big Carlos Pass the range was 5,600 to 59,000 cells/L.

Saunders et al. (1967) found that the ubiquitous estuarine diatom, *Skeletonema costatum*, was the dominant species throughout the year for the entire study area. Counts of up to 100,000 cells/mL were recorded. Other species such as *Chaetoceros* spp., *Asterionella japonica*, several *Rhizosolenia* spp., and *Bellerochea malleus* were also common, but the dynamics of *Skeletonema* appeared to control community composition.

Steidinger (1972, 1973) delimited four broad phytoplankton assemblages for the Gulf: (1) estuarine, (2) estuarine and coastal, (3) coastal and open Gulf, and (4) open Gulf. Species composition of the first three groups tended to blend with one another, although *Ceratium* spp. and *Rhizosolenia* spp., among others, showed close associations. In estuarine and coastal waters, unidentified microflagellates (<15 μm) numerically dominated the community. Coastal and open Gulf waters were characterized by 10 dinoflagellate and 8 diatom species, all eurythermal and euryhaline. No seasonal or successional study of the coastal or shelf phytoplankton community is available except for the *Memoirs of the Hourglass Cruises* reports on dinoflagellates (Steidinger and Williams 1970) and diatoms (Saunders and Glenn 1969). Numerical abundance in the coastal open Gulf region is often one to two orders of magnitude lower than in estuarine regions.

Oceanic/Shelf Waters. The open Gulf assemblage is more distinct, being characterized by species common to most tropical and subtropical oceanic regions (e.g., the dinoflagellates *Amphisolenia*, *Heterodinium*, and *Pyrocystis* and the diatoms *Ethmodiscus*, *Gossleriella*, and *Planktoniella sol* [Steidinger 1973]). The cyanobacterium *Trichodesmium* (*Oscillatoria*) is common in shelf and open Gulf waters. As a nitrogen fixer (Carpenter and Price 1977), this species may play a significant role in nutrient cycling on the West Florida shelf and Straits of Florida.

Ivanov (1966) described 128 taxa, based on net tows and water-bottle samples, from a transect into the western and southern Gulf of Mexico during October-November 1964. Trichomes of the cyanobacterium *Trichodesmium* predominated, although no quantitative information was given. *Trichodesmium* and unidentified microflagellates

contributed approximately 73 and 44%, respectively, of the total carbon at Station 252 in the Gulf (no location given, Hobson and Lorenzen 1972). At two stations occupied during *Alaminos* cruise 72-A-12 (Stations 8 and 9: 24.51°N, 83.12°W and 24.13°N, 85.56°W, respectively), *Oscillatoria erythraeum* (= *Trichodesmium erythraeum*) and various species of the dinoflagellate genus *Ceratium* were numerical dominants (El-Sayed and Turner 1977). Ortner et al. (1984) occupied a fixed station at 25°30'N, 87°00'W in the Loop Current for eight days (30 January to 6 February). During this period, a high pressure system moved through the area, with a dramatic increase in wind-speed and a deepening of the mixed layer from 20-40 m to 110-120 m. Average total abundance decreased from 20,000 to 10,000 cells/L at the depth of maximum productivity, but the relative abundance of two coccolithophorids (*Emiliana huxleyi* and *Gephyrocapsa oceanica*) increased during 1 to 5 February. The authors suggest that deep vertical mixing may have introduced a pulse of inorganic nutrients into the euphotic zone, which allowed an increase in the relative abundance of these two species. Although *Trichodesmium* may be dominant in surface waters, coccolithophorids are often most abundant in deeper layers of the open Gulf (Steidinger 1973). Similar results were reported by Yoder and Mahood (1983) for samples collected in the subsurface chlorophyll maximum along several cross-shelf transects of the West Florida shelf from approximately 83° to 85°W between 25° and 27°N. During the spring cruise (April), coccolithophores dominated numerically throughout the water column, with population levels on the order of 10^4 to 10^5 cells/L. Abundance of this group, primarily *E. huxleyi*, increased in the subsurface chlorophyll maximum. In summer (September), a low salinity lens was found throughout the study area. Seaward of this lens, coccolithophores at population levels of 5×10^5 cells/L were dominant. Within the lens, diatoms were dominant, particularly *Rhizosolenia alata* which accounted for 80% of the total diatom cells. Coccolithophores or diatoms other than *R. alata* were dominant in the subsurface chlorophyll maximum.

Straits of Florida

Nearshore Waters. Information on phytoplankton community composition and abundance for nearshore waters in the Straits of Florida region is limited to a few studies of epiphytic diatoms on seagrasses and coral reefs. A study conducted in Biscayne Bay, north of the study area, is incorporated because it is the only one available for embayments in this region.

Epiphytic diatoms growing on blades of the seagrass *Thalassia testudinum* were identified and counted in samples collected in 1964 to 1965 from Biscayne Bay, Bear Cut, Southwest Point on Key Biscayne, Soldier Key, and the Ragged Keys (Reyes-Vasquez 1970). Tabular data on species, with their temperature and salinity of occurrence, were presented. Seasonal abundance from the Biscayne Bay and Bear Cut stations indicates increasing numerical abundance from November through March, a decrease in April, increasing again to a maximum in June-July. Maximum populations at Biscayne Bay were on the order of 12,000 cells/cm^2, whereas levels at Bear Cut were 5,000 cells/cm^2. No interpretation of the difference was made.

Miller et al. (1978) and Montgomery et al. (1978) surveyed the diatom communities at Sambo Reef off Key West, Sombrero Reef off Marathon, and Molasses Reef off lower Key Largo. Substrates from various areas on the reef (living coral), adjacent coral sand, and nearby *Thalassia testudinum* blades were sampled and compared qualitatively for dominants and quantitatively by diversity, evenness, and similarity indices. Corals were characterized by an assemblage of *Campylodiscus* sp., *Podocystis* sp., and *Triceratium* sp., with *Amphora* and several *Diploneis* spp. numerically dominating the coral sand community and *Mastogloia* spp. on *Thalassia* blades. Population densities ranged from 10^3 to 10^5 cells/cm^2 of surface area. Similar habitats at different reef sites displayed

comparable diversity and similarity indices. Attached diatom diversity increased with the structural complexity of the habitat. The authors suggested that diatom flora may play a significant role in carbon cycling in reef areas and may also be used as an index of favorable or unfavorable biotic conditions. Decreased diatom diversity or elevated diatom biomass could be used as an indicator of nutrient enrichment which is unfavorable for coral reef maintenance and survival.

The study by Brand (1988) in Biscayne Bay represents the only comprehensive phytoplankton program carried out in this region. Population assessments were a minor part of the study, although the community was characterized in terms of picoplankton, diatoms, and dinoflagellates. Total population abundance had a maximum at 8 to 11 million cells/L depending upon the fixative used for preservation. Cell concentrations decreased from north to south, with seasonal averages in the northern sections being five-fold higher than in southern sections. Small coccoid cells (picoplankton) were dominant throughout the bay, comprising 80% of the total cells in north Biscayne Bay and 90% in south Biscayne Bay with concentrations of 4 to 5 million and 1 to 2 million cells, respectively. Centric diatoms contributed 10 to 20% of the community in the north and 1% or less in the south. Dinoflagellates were a minor component of the community throughout the bay. Brand (1988) concluded that Biscayne Bay was a eutrophied system, limited by phosphate. The major input of nutrients, including phosphate, occurred by land runoff, but Brand (1988) suggested that the removal of phosphate by adsorption onto limestone led to limitation by this element.

Oceanic/Shelf Waters. No reports of phytoplankton community structure or species composition and abundance are available for the Straits of Florida section of the study area. An early study by Collier (1964) sampled six stations in the Straits of Florida at several depths, including the estimated depth of maximum primary production (80 to 90 m), but used serial dilution methods to determine abundance and dominants. Thus, only those species that would grow in the particular medium were found. His general conclusion was that microdiatoms (*Chaetoceros galvestonensis* and *Chaetoceros* sp.) were numerical dominants at all stations in March-April and again in June. Unidentified coccoid forms were also abundant in June, whereas microflagellates were important whenever microdiatom populations declined.

Two transects from Havana, Cuba to the tip of Florida were sampled by Ivanov (1966). No specific locations were given. The cyanobacterium *Trichodesmium* was most abundant, with the exception of one station where populations of the diatom *Thassiothrix frauenfeldii* were extant. Of the 52 taxa recorded, representative species included the diatoms *Rhizosolenia hebetata* and *R. styliformis*, *Chaetoceros affinis* and *C. pendulus*, the dinoflagellates *Ceratium fusus*, *C. tripos* and *C. vultur*, and *Pyrocystis* spp. Qualitative tabular data were provided, but no quantitative information was presented.

Miller et al. (1953) and Bsharah (1957) demonstrated that nanoplankton were dominant in the Straits of Florida, based on chlorophyll and dry weight, respectively. Miller et al. (1953) provided the first description of subsurface chlorophyll maxima at his station 18 km (10 nmi) east of the Miami sea buoy. The two-year study reported by Vargo (1968), and used by Walsh (1969) to compare phytoplankton standing crop in the Antarctic to that of the Straits of Florida, presented total cell counts based on fluorescence methods, but no community composition data. Two stations occupied during this study were within the study area: West Channel (24°30'N, 80°30'W) and Alligator Reef (24°50'N, 80°30'W). All stations exhibited a pronounced seasonal cycle with a standing crop maximum at all stations during the same time of year. Vertically integrated counts were highest in the winter-spring months, with low values occurring during summer. The seasonal average at West Channel was 3.21 x 10^{12} cells/m^2 in 1964 and two-fold higher in 1965 to 1966. Similar population levels were found at Alligator Reef, a much

shallower location. Subsurface maxima in counts were consistently found and were always associated with a thermocline. There was essentially no difference between all stations in the yearly average integrated standing crop, although three hydrographically distinct regions were sampled. Vargo (1968) concluded that vertical water movements and influx from other regions acted in concert to yield the seasonal cycles in abundance.

Biomass (Chlorophyll *a*) and Production

Gulf of Mexico

Nearshore Waters. A summary of the primary productivity values available for the Gulf of Mexico and the Straits of Florida is presented in **Table 6.1.** The earliest production value for the Gulf/Straits region is by Riley (1938), based on changes in oxygen in light and dark bottles. His value of 0.2 g $C/m^2/d$ is the only estimate available for the shallow waters of the Dry Tortugas. Kondratyeva and Sosa (1966), using carbon-14 uptake in coastal and offshore waters off the northwest coast of Cuba (from 22° N to 23° N between 83° W and 85° W) found a range of 19 to 33 mg $C/m^3/d$ for waters <5 m deep. The annual average for coastal areas was 28 g C/m^2. No biomass estimates were presented. Data from the Charlotte Harbor area (Squires 1984), which is north of the study area, are the only information available for embayments on the Gulf coast close to the study area. Chlorophyll and primary productivity in this estuary followed similar seasonal trends, being highest during late summer-fall and decreasing through late winter. Chlorophyll concentrations ranged from 2.6 $\mu g/L$ near the mouth of the estuary to 47 $\mu g/L$ as an annual maximum within the embayment. Annual integrated surface primary production ranged from 126 g C/m^3 at the mouth to 227 and 224 g C/m^3 within the bay.

Oceanic/Shelf Waters. Steele (1964) provided some of the earliest data on phytoplankton biomass and production in the Gulf of Mexico. Data from a transect run along 25° N indicate a rise in the 20° C isotherm to above 75 m, with concomitant increases in phosphate concentration and chlorophyll. Chlorophyll concentrations of 0.2 mg/m^3 and greater, between 40 and 75 m, were associated with the intrusion. Two other stations were occupied for assessment of primary production using carbon-14 uptake (24° 57'N, 84° 08'W on 24 April 1962; and 24° 53'N, 84° 39'W on 25 April 1962). Both showed subsurface chlorophyll maxima between 75 and 100 m that exhibited a day-night periodicity in depth and concentration. Average maximum production (mg $C/m^3/h$) in surface water (5 m) was 0.37; at 50 m, 0.43; and at 100 m, 0.43. The latter value must be in error, because measured rates for three experiments were 0.60, 0.57, and 0.43, which give an average for 100 m of 0.53. All values should be viewed with caution because they were determined using artificial light on shipboard during 4-h incubations. However, based on the chlorophyll distribution, day-night periodicity, chlorophyll-to-carbon ratios, and the production rates, Steele concluded that the subsurface chlorophyll maximum was attributable to living cells that increased their chlorophyll content rather than an accumulation of cells due to sinking.

In addition to production rates in nearshore Cuban water, Kondratyeva and Sosa (1966) reported values for "oceanic waters," normally 18.5 to 22 km (10 to 12 nmi) offshore with depths >100 m. Few vertical or light profiles were made; rather, surface production was related to productivity at various depths (light levels) through the use of coefficients determined from two vertical profiles. In September 1964, surface (0 to 5 m) rates were on the order of 1.6 to 6.7 mg $C/m^3/d$, which yielded integrated water column areal rates of 0.5 to 0.75 g $C/m^2/d$. Rates in November-December were reduced considerably to surface values of 0.8 to 1.1 mg $C/m^3/d$ and integrated totals of 0.16 to 0.19 g $C/m^2/d$. By comparison, a value of 5.16 mg $C/m^3/d$ can be calculated from

Table 6.1. Primary production rates for the Gulf of Mexico and the Straits of Florida.

Reference	Volumetric Rate		Areal Rate	
	mg C/m^3/h	mg C/m^3/d	g C/m^2/d	g C/m^2/yr
COASTAL GULF OF MEXICO				
Riley (1938)			0.20	
Kondratyeva and Sosa (1966)		19-33		
Squires (1984)	12-279			
COASTAL STRAITS OF FLORIDA				
Jones (1963)			0.02-0.06	
Brand (1988)	2-17			
OFFSHORE GULF OF MEXICO				
Steele (1964)	0.37-0.43			
Kondratyeva and Sosa (1966)		1.6-6.7	0.50-0.75*	160
		0.8-1.1	0.16-0.19†	
Belousov et al. (1966)			0.50-1.00	
Steidinger (1973)			0.06-0.10	27
El-Sayed and Turner (1977)			0.30-0.34	
Ferguson and Sunda (1984)	0.11-0.2			
Ortner et al. (1984)	0.12-0.5			
Yoder and Mahood (1983)			0.10-0.80	
Vargo et al. (1987)			0.30-0.50§	
			0.80-2.90¶	
OFFSHORE STRAITS OF FLORIDA				
Corcoran and Alexander (1963)			0.50	

* Rates for September 1964.
† Rates for November to December 1964.
§ Open Gulf waters, non-bloom periods.
¶ Range of measured and calculated rates in red tide blooms.

Steele's (1964) rate of 0.43 mg/C/m^3/h, assuming a 12-h day. Kondratyeva and Sosa (1966) computed an annual average for the deepwater sections as 160 g C/m^2. Another Soviet investigator considered the effects of the Loop Current on productivity of the Southwest Florida shelf. Belousov et al. (1966, cited by Yoder et al. 1983) identified regions of "medium to intensive upwelling" and zones of high production along the southwest tip of the West Florida shelf at about 25 ° N. Primary production in these areas was estimated at 0.5 to 1.0 g C/m^2/d. The values were considered to be high relative to other regions in the Gulf and were attributed to upwelling caused by undefined processes.

Most stations established by Hobson and Lorenzen (1972) appear to be outside the study area, although no locations are given. Their study, dealing with the relationship between vertical chlorophyll distributions and the density structure of the water column, concluded that subsurface chlorophyll maxima were influenced by and associated with the depth of the pycnocline. The concentration of chlorophyll in maxima was patchy throughout the region, but in 1968 most all subsurface maxima were found between 50 and 90 m, whereas in 1969 they were only found at 60 m.

Steidinger (1973) summarized data from a number of sources, including El-Sayed (1972) for chlorophyll and productivity in various regions of the Gulf of Mexico. Chlorophyll *a* concentrations, corrected for phaeopigments, ranged from 10 to 16.5 mg/m^2 for the central and western Gulf, as well as inshore Gulf waters; values for the entire Gulf were about 0.2 mg/m^3. Daily productivity values were estimated at 0.06 g C/m^2/d for the entire Gulf and 0.1 g C/m^2/d for the eastern Gulf. Such values

are lower than earlier estimates. An annual value of 27 g C/m^2 calculated by El-Sayed (1972) was used by Walsh (1983) for carbon budget estimates.

Additional chlorophyll and primary production measurements for specific locations were given by El-Sayed and Turner (1977). Stations 8 and 11 for cruise 72-A-12 (23 June to 3 July 1972) were located at 24.51°N, 83.12°W and 23.02°N, 85.12°W, respectively. Chlorophyll concentrations were 0.1 to 0.2 mg/m^3, with integrated production rates of 336 and 300 mg C/m^2/d, respectively. Size fractionation of chlorophyll and primary production was done during a 1973 cruise. The <20 μm size fraction accounted for 65.1 to 93.4% (mean = 83%) of the standing crop and 51.8 to 99.9% (mean = 83%) of the total production. Such values are similar to those reported by Malone (1971, 1980) for other regions and emphasize the importance of the nanoplankton size fraction in the phytoplankton community.

The first use of "clean techniques" for primary production measurements in the Gulf, as recommended by Carpenter and Lively (1980) and Fitzwater et al. (1982), was by Ferguson and Sunda (1984) and Ortner et al. (1984). Ferguson and Sunda (1984) reported rates of 0.11 and 0.2 μg C/L/h, respectively, for a Gulf Loop station (25°25'N, 86°59'W) and a Yucatan station (23°34'N, 87°49'W). Ortner et al. (1984) calculated integrated rates (0 to 90 m) of 14 and 62 mg C/m^2/h, respectively, for 31 January and 5 February. The latter value was measured after the mixing event reported in a previous section. Inspection of their Figures 2 and 3 produces a range of values of 0.12 to 0.5 μg C/L/h for vertical profiles measured before and after the mixing event and are comparable to those measured by Ferguson and Sunda (1984).

The most extensive data set for the West Florida shelf/Loop Current system was obtained by Yoder and Mahood (1983) during the Southwest Florida Shelf Ecosystems Study, Year 2 Modification conducted for the Minerals Management Service. The study was designed to assess the importance of Loop Current frontal eddies to primary production on the West Florida shelf. A series of cross-shelf and along-shelf transects was sampled within a region bounded by 24° to 27°N and 82° to 85°W during spring (1 to 7 April 1982) and summer (13 to 17 September 1982). Eastward movement of Loop Current eddies was associated with subsurface upwelling of nutrient-enriched water into the euphotic zone during both cruises, with the top of the nitracline located at depths of 40 to 60 m. A subsurface chlorophyll maximum was associated with the top of the nitracline, with maximum concentrations of 0.2 to 1.2 mg/m^3 compared with surface values of 0.1 mg/m^3. During the spring cruise, the mean production at all depth ranges (<100 m, 100 to 200 m, and >200 m) was essentially the same, at 0.5 g C/m^2/d. However, for stations located seaward of the 200-m isobath and within the influence of the intrusion, the average water column production was 0.6 g C/m^2/d, whereas for three other stations located outside the eddy-induced upwelling area, production averaged 0.1 g C/m^2/d. Thus, subsurface upwelling may enhance phytoplankton primary production by as much as six-fold. Similar results were reported for the summer cruise. Production within the 100- to 200-m isobath averaged 0.8 g C/m^2/d (the area affected by intrusion of nutrient-rich water into the euphotic zone), while rates seaward and shoreward of the 200-m isobath were 0.3 and 0.4 g C/m^2/d, respectively. Concomitant increases in chlorophyll were found during both cruises. Subsurface chlorophyll maxima were usually associated with the depth of maximum productivity.

The effect of Loop Current intrusions on primary productivity on the Southwest Florida shelf was addressed by Yoder et al. (1983). Total water column, depth-integrated primary production was linearly related to the amount of chlorophyll *a* in the subsurface maximum. Although the frequency of eddy-induced intrusions is not known (Paluszkiewicz et al. 1983), Yoder et al. (1983) used information from Vukovich et al.

(1979) to estimate that eddy-induced upwelling occurs no more than 50% of the time at 25 ° N. Use of the average production rate obtained during the April study (0.5 g C/m^2/d) suggests that annual production associated with eddy-induced upwelling may be 90 g C/m^2, or roughly three-fold greater than previous estimates for other areas of the Gulf (El-Sayed 1972; Walsh 1983). Until additional information on eddy frequency, duration, and extent is known, the contribution of this phenomenon and its role in the production cycle on the West and Southwest Florida shelf remain uncertain.

Episodic red tide events may also be a significant source of carbon for the West Florida shelf (Vargo et al. 1987). Blooms of the toxic dinoflagellates in shelf waters may encompass areas from 5,200 to 12,400 km^2. Shelf production values during non-bloom periods for areas north of Tampa Bay ranged from 0.3 to 0.5 g C/m^2/d in waters <100 m deep. These values are comparable to those reported by Yoder and Mahood (1983) for depths <100 m (0.4 g C/m^2/d). Based on measured values and rates calculated from laboratory measurements and Coastal Zone Color Scanner chlorophyll estimates, production rates during red tide blooms ranged from 0.8 to 2.9 g C/m^2/d, with an average of 1.9 g C/m^2/d. Vargo et al. (1987) used the average production estimates and a one-month bloom duration to estimate that red tide blooms may contribute 40% of the annual shelf primary production. They felt that this value was high, but suggested that production from this source could be a significant input into the shelf ecosystem.

Straits of Florida

Nearshore Waters. Information for inshore waters in the Straits of Florida region is limited to two reports. An early study by Jones (1963) reported primary production rates based on oxygen light-dark bottle incubations made on patch reefs south of Miami. For reefs off Sand Key and Elliot Key, production rates were in the range of 0.06 and 0.02 g C/m^2/d for gross and net production, respectively. Because total water column primary production, based on net diurnal oxygen changes in the water column, yielded rates that ranged from 0.9 to 1.9 g C/m^2/d in November and March, Jones concluded that phytoplankton were minor contributors to primary production in the shallow patch reef areas and that benthic seagrasses and macroalgae were the major primary producers.

Brand (1988) described biomass, primary production, nutrient bioassay, and related parameters for an annual cycle in Biscayne Bay, adjacent to the current study area. Chlorophyll concentrations varied spatially from the north to the south end of the bay, from approximately 3.0 to 0.2 μg/L. High chlorophyll levels were associated with lower salinities, which suggested that runoff from land was the major source of nutrients for blooms in the bay. Phytoplankton in the <5-μm size fraction contributed 60% of the biomass in the north end of the bay and 80% of the biomass in the south end. Primary productivity showed similar trends. Production was 5 to 8 times higher in the north than in the south, with production rates of 17 and 2 μg C/L/h, respectively. Assimilation numbers averaged about 10 mg C/mg chl/h throughout the bay. Assimilation numbers of this magnitude indicate that the phytoplankton were not nutrient limited. Therefore, Brand (1988) suggested "that ultimately it is the low standing stock biomass of phytoplankton that limits planktonic productivity in the bay" and that benthic algae and seagrasses, especially in south Biscayne Bay, were the dominant primary producers.

Oceanic/Shelf Waters. There is no recent literature available to characterize phytoplankton biomass or primary production in the Straits of Florida study area. Data from publications which cover the period from 1953 to 1972 suffer from a lack of consistent methodology. This makes data comparisons difficult except in a general sense.

An early study by Miller et al. (1953) established seasonal variation in chlorophyll and vertical heterogeneity at a station located 18.5 km (10 nmi) east of the Miami sea buoy. Both shallow and deep chlorophyll maxima were found (25 and 175 m). Nanoplankton (retained by a Whatman No. 54 filter paper) were 1,200 times more abundant than net plankton (Clark-Bumpus), establishing this size fraction as the dominant members of the phytoplankton community.

Bsharah (1957) confirmed the dominance of nanoplankton (in this case particles <107 μm) in monthly samples collected at a station 74 km (40 nmi) east of Miami (25°33'N, 79°25'W). Nanoplankton outweighed net plankton by a ratio of 1,000:1, based on lyophilized dry weights. Summer maxima (July-August) were found in the upper 35 m, and varied inversely with nutrient concentration (nitrate and phosphate).

Alexander et al. (1961) compared the vertical and seasonal distribution of chlorophyll (measured at the same station occupied by Bsharah 1957) with values obtained from Bermuda and the North Sea. The Straits of Florida area, with a seasonal range of undetectable to 0.3 μg chl/L, was described as "tropical." Water column subsurface maxima occurred in summer (June-July), with concentrations in excess of 0.5 μg/L between 75 and 100 m.

Subsurface chlorophyll maxima were studied by Alexander and Corcoran (1963) while following a drogue deployed at 100 m between Miami and Cape Canaveral. The subsurface maximum was found between 40 to 60 m and was associated with the changing position of the 24.00 sigma-t surface. Concentrations were about 0.3 μg/L. Total pigment in the water column, however, remained relatively constant over the path of the drogue at about 36 mg/m^2.

The first study incorporating primary production measurements in offshore waters of the Straits of Florida was conducted by Corcoran and Alexander (1963) at Cat Cay station, the same station occupied by Bsharah (1957). The permanent thermocline was located between 120 and 140 m, with a seasonal thermocline at 100 m in winter. Nutrient and chlorophyll concentrations were within the range of and displayed similar seasonal patterns as previous studies (Bsharah 1957; Alexander et al. 1961). Low standing stocks of nutrients combined with the deep mixed layer led Corcoran and Alexander (1963) to conclude that remineralization processes determined the availability of nutrients and controlled phytoplankton biomass and production.

Primary production values were only available for April through August 1960 during the Corcoran and Alexander (1963) study. Highest carbon-14 incorporation rates were observed between 25 and 100 m, but no correlation was found between productivity and chlorophyll concentration. Corcoran and Alexander (1963) implied that the maximum production rate of 0.5 g C/m^2/d was found in April, although maximum chlorophyll concentration was found in June. They estimated that annual production was at least equal to that found in the Sargasso Sea (72 g C/m^2), but it is unclear how they arrived at this conclusion.

Two additional studies are relevant to the phytoplankton dynamics in the Straits of Florida, although they were also conducted north of the study area. Morris et al. (1971) assessed the use of ammonia-enhanced dark carbon-14 uptake as a method to determine nitrogen deficiency in cultures and natural phytoplankton populations. Natural populations in the Straits of Florida did not exhibit ammonia-enhanced dark carbon-14 uptake; however, after one to two days incubation in carboy cultures, elevated ammonia-enhanced dark uptake occurred. This suggests that the available nitrogen was rapidly depleted and the populations became nitrogen-limited. The authors concluded that

while Straits of Florida phytoplankton were not nitrogen deficient, the low nitrogen levels, coupled with slow regeneration rates, would limit biomass. Yentsch et al. (1972) measured the activity of alkaline phosphatase, an enzyme that enables use of organic phosphorus sources by phosphorus-deficient cells, in the cyanobacterium *Oscillatoria erythraea* (*Trichodesmium*) collected in the Straits of Florida. The alga exhibited high alkaline phosphatase activity, indicating potential inorganic phosphorus deficiency, but not necessarily phosphorus limitation, because organic sources could be used. Because this species can also fix nitrogen (Carpenter and Price 1977), its growth would not necessarily be limited in nitrogen- and phosphorus-deficient environments (e.g., the Straits of Florida and Gulf of Mexico).

Discussion

Several aspects of the data summarized in the previous section demonstrate features of the phytoplankton community and its dynamics that are common to both the Gulf of Mexico and Straits of Florida sections of the study area.

Importance of *Trichodesmium*

Populations of the cyanobacterium *Trichodesmium* may be an important component in the large size fraction of the phytoplankton community. The ability of this alga to fix nitrogen and utilize organic phosphorus gives it a competitive advantage over other classes of phytoplankton in the oligotrophic waters common to the Gulf and Straits of Florida. Mass blooms of this species occur in the Gulf of Mexico from spring to fall (Steidinger 1973). It may contribute 20% of the water column production in the Caribbean (Carpenter and Price 1977), with photosynthetic rates of 22 mg $C/m^2/d$ which are on the same order as reported for both nearshore (Jones 1963) and offshore waters (Steidinger 1973) in the study area. This species is most commonly found in the upper 50 m of the water column, with maximum abundance in the top 20 m (Carpenter 1983). Extensive rafts or mats of cells accumulate at the surface due to the production of gas vacuoles. These rafts have been observed to cover large areas in the Gulf (K. Steidinger, pers. comm. 1988, Florida Department of Natural Resources, St. Petersburg; G. Vargo, pers. observ.). *Trichodesmium* must be considered a key species in the Gulf of Mexico/Straits of Florida phytoplankton community.

Importance of Microflagellates and Nanoplankton

Microflagellates and nanoplankton were noted as the numerically dominant size fraction in the phytoplankton community in coastal embayments, nearshore waters, and offshore waters of the Gulf of Mexico and Straits of Florida. In oceanic waters, this group may contribute 75% or more of the biomass and 80% of the primary production (Malone 1971, 1980; El-Sayed and Turner 1977). The maximum photosynthetic rate per unit chlorophyll and photosynthetic efficiency tend to be greater in nanoplankton than in net plankton (Malone 1980). Growth rates of nanoplankton were on the order of 1 to 2.5 doublings per day in tropical Pacific waters (Bienfang and Takahashi 1983). Ammonia uptake rates for these populations were 75% greater than that of the 3- to 20-μm size fraction. The preference for ammonia rather than nitrate as a nitrogen source for nanoplankton is indicative of their dominance in steady-state, oligotrophic waters where ammonia excretion by zooplankton can be a significant source of nitrogen (Malone 1980; Harrison and Wood 1988). Reduced sinking rates of this group (Bienfang and Takahashi 1983) combined with enhanced ability to rapidly uptake and utilize organic nitrogen to maintain high growth rates allows nanoplankton to easily maintain their biomass. If sinking rates are negligible, then this group can contribute a

proportionately greater share of the community net production (Bienfang and Takahashi 1983). Their importance to higher trophic levels thus becomes increasingly significant.

Subsurface Chlorophyll Maxima

For the Gulf of Mexico and Straits of Florida region, subsurface chlorophyll maxima (SCM) apparently predominate in the vertical water column distribution of populations, biomass, and production. These phenomena are characteristic of coastal and oceanic waters worldwide (e.g., Vandevelde et al. 1987). The mechanisms responsible for such maxima were reviewed by Cullen (1982). Most SCMs are associated with the nutricline and stable isopycnal surfaces (Eppley et al. 1979; Herbland and Voituriez 1979; Yoder et al. 1983). Legendre et al. (1986) postulated that phytoplankton associated with nutriclines had enhanced production due to matching or resonance of physical scales with biological scales. As noted by Vandevelde et al. (1987), Lewis et al. (1983) demonstrated that the presence of SCMs can increase thermal stratification at the deeper portion of the maxima, thus enhancing stability and confirming possible resonance of physical scales with biological scales.

On the West Florida shelf, cyclonic frontal eddies form on the eastward boundary of the Loop Current, travelling southward with a frequency of 2 to 14 days (Paluszkiewicz et al. 1983). In the northern Straits of Florida and the southeastern shelf region, northward moving cyclonic eddies cause persistent upwelling of nutrient-rich water onto the shelf (Lee et al. 1981). SCMs and enhanced production are associated with this upwelling. Yoder (1985) concluded that it is the major process affecting phytoplankton dynamics on the outer southeastern shelf. In the Gulf of Mexico, Yoder et al. (1983) found that total water column production was linearly related to the amount of chlorophyll in the SCM. Given the apparent low productivity of Gulf surface waters, the SCM would appear to be the primary feature affecting production on the West Florida shelf. Eddy formation and subsequent upwelling of nutrient-rich water into shelf regions on the western edge of the Florida Current in the southern portion of the Straits of Florida is undemonstrated. Temperature and sigma-t diagrams presented by Vargo (1968) for his Alligator Reef and West Channel stations suggest that seasonal upwelling occurs in this region. Its effects on the phytoplankton community and carbon fluxes in the area are undetermined.

Primary Production Rates

Primary production rates for the South Florida region are summarized in **Table 6.1.** The lack of specific information on the methodology makes it impossible to convert volumetric rates to areal rates; therefore the values are listed as reported in the various papers. Areal production rates span almost two orders of magnitude. The disparity may be the result of differences in methodology, time of year, bloom versus non-bloom conditions, location, and experimental conditions. A comprehensive program based on consistent methodology and reasonable time intervals is necessary to provide sufficient data to assess annual production in the Gulf and Straits of Florida region.

Conclusions

Water column studies, particularly studies of plankton dynamics, have traditionally not been included in investigations of environmental effects of oil and gas exploration and development. The commonly held view is that any effects that occur in open water will be short-lived because current transport will disperse the pollutant and re-inoculate the area with a similar community. While this reasoning may have merit in the event of a single, catastrophic event (e.g., major oil spill), it is not valid for chronic, low-level

inputs. Chronic input of No. 2 fuel oil to the Marine Ecosystems Research Laboratory (MERL) mesocosms affected herbivore populations (planktonic and benthic zooplankton and benthic filter feeders), which led to a dramatic increase in phytoplankton biomass and production (Elmgren et al. 1980). Subtropical and tropical, oligotrophic waters such as those of the Gulf of Mexico and Straits of Florida have tightly coupled food webs. Steady-state phytoplankton biomass and productivity are maintained by zooplankton grazing and nutrient excretion ("regenerated productivity" *sensu* Dugdale and Goering 1967). Thus, these ecosystems may be extremely vulnerable to perturbations at lower trophic levels. The paucity of information on water column ecosystems for the Gulf of Mexico and Straits of Florida does not allow a definitive ecological characterization of the area or the establishment of trophic structure and interactions, except on a theoretical level. Therefore, we cannot predict the effects of oil and gas operations on the primary producers of this region except on a theoretical level.

There are no reports regarding annual cycles of phytoplankton composition and numerical abundance for the coastal, shelf, and outer-shelf waters within the study area, nor for regions that bound the study area. Ecologists, physiologists, fisheries biologists, and other researchers have become increasingly aware that particular phytoplankton species are important from the standpoint of processes and trophic interactions; primary production measurements, which average the community response, do not provide a complete ecological picture. The seasonality and raft formation of *Trichodesmium*, combined with physical transport mechanisms, are particularly important because this species seems to be a dominant within the region and is an important component in the nitrogen cycle. Oil and gas exploration or development activities that affect surface waters could have substantial consequences for production and nitrogen fixation by this organism.

Short-term studies of the annual and inter-annual variation in phytoplankton species composition and abundance should be coupled with the acquisition of basic primary production and biomass measurements. The lack of such information precludes an accurate assessment of annual production in the region. Such a program should be designed to determine onshore-offshore gradients in abundance, biomass, and production along the West Florida shelf and the Straits of Florida. Emphasis on regions of shelf-break upwelling along the West Florida shelf and potentially in the Florida Keys would provide preliminary information about the effects of nutrient inputs from this source on primary production and species composition. Short-term (i.e., daily) measurements at selected locations and seasons should be included to interpret the potential variability of monthly measurements.

Such basic ecological topics as nutrient uptake, grazing, and nutrient remineralization and recycling have not been studied within coastal or shelf waters for this region. Models based on constants derived from literature values from other systems need re-examination (Walsh 1983), particularly because annual primary production estimates need to be increased by a factor of three or more from the standard literature value of 30 g C/m^2. The two cruises undertaken by Woodward-Clyde Consultants and Skidaway Institute of Oceanography (1983) represent the most complete data set for primary production in the region. However, measurements were only made over approximately a two-week period. An annual cycle with monthly measurements, at a minimum, is required for coastal, mid-shelf, and shelf break regions for the Gulf and Straits of Florida areas. This should include a time-series with daily measurements in areas of upwelling to determine the frequency and duration of intrusions and their relationship to shelf production.

Information on sediment/water column interactions is needed. Inputs of nutrients, particularly nitrogen, via upwelling processes, water column recycling, sediment re-mineralization, and fluxes must be addressed, especially for the West Florida shelf region. No information is available on these processes. Fanning et al. (1982) noted that the shallow waters of the West Florida shelf can be mixed to the sediment-water interface with subsequent release of nutrients. They suggest that "resuspension of 1 mm of shelf sediment could intermittently augment overlying productivity by as much as 100 to 200%." Nutrient additions to the water column from sediment resuspension, particularly during seasonal storm events, may therefore be an important source of recycled nutrients for maintenance of primary production on the shelf. This suggests that information on sediment/water column interactions is needed before commercial activities that could affect sediments within the region are carried out.

Long-term programs are required to address the processes noted in the preceding paragraphs. A study of nitrogen dynamics within the region would address questions such as the following:

- What is the duration, frequency, and areal extent of shelf-break upwelling events, and what annual nitrogen input is associated with these events?
- What is the role of sediment nutrient mineralization in the dynamics of nitrogen and other nutrients of the region?
- Do storm events contribute significant amounts of nitrogen and other nutrients to the water column along the West Florida shelf?
- Is nitrogen fixation by *Trichodesmium* a significant source of nitrogen for oligotrophic shelf waters?
- Are macroalgae, particularly the populations found in deep water near the shelf break, a significant sink for nitrate input associated with upwelling events? What is their contribution to total primary production in the region?
- What is the role of nutrient excretion and grazing by zooplankton in primary production for the region?
- What is the ecological role of toxic red tides on the West Florida shelf? Do they contribute a significant fraction of the annual primary production to the region? Do they act as regulator of the shelf ecosystem by affecting higher trophic levels (e.g., causing the death of demersal and pelagic fish, thereby shifting carbon flow in the system through detrital pathways)? Or are these episodic events of such minor scale and duration that they have little consequence for the functioning of the ecosystem?

Information obtained through studies designed to answer these questions would allow a re-examination of the preliminary ecosystem model developed by Walsh (1983). Such an ecosystem model must be coupled to an adequate physical circulation model if it is to provide useful and ecologically relevant information.

Transport of phytoplankton populations from the West Florida shelf to the east coast of Florida and northward are known from the appearance of *Ptychodiscus brevis*, the toxic red tide dinoflagellate normally only associated with Gulf waters, on the east coast of Florida (Murphy et al. 1975; Roberts 1979) and in North and South Carolina waters (Tester et al. 1989). Early drift bottle studies by Williams et al. (1977) indicated

that movement of water from the West Florida shelf through the Straits of Florida occurred. Particles, whether living or not, that can be maintained in the water column, can therefore be transported from the Gulf of Mexico to regions along the east coast of Florida and northward. To the best of my knowledge, there is no information available on the frequency of entrainment of this red tide dinoflagellate or of other living particles, or on the mechanisms responsible; it is not known whether there are physical water masses that remain coherent for some period of time, or whether they are simply mixing events.

The transport of red tide organisms from the Gulf of Mexico to North and South Carolina demonstrates that oceanic and coastal ecosystems are a continuum, rather that isolated entities; events that occur in one region can and do affect other areas. Our current understanding of how modifications in one part of a system may affect other regions along the continuum is rudimentary at best. Therefore, any activities that have the potential for effects on components of the system should be approached with caution.

ZOOPLANKTON

Thomas L. Hopkins

Taxonomic Dominants

Taxonomic dominants of the three marine provinces (oceanic, shelf, and nearshore) can be considered as indicator species of each water mass. Furthermore, the zooplankton from each marine province can be categorized by whether they are permanent residents of the plankton (holoplankton), members of the plankton for only part of their life cycle (meroplankton), or species that are accidental/temporary (tychoplankton/hypoplankton) members of the plankton. The last group consists of mainly benthic forms and as such will be considered in only the nearshore section.

The above ecological categorizations are more appropriate for open-ocean and shelf waters than for estuaries where dominant holoplanktonic genera, such as the copepods *Acartia* and *Labidocera*, have resting eggs that reside for a time in the sediments (Kasahara et al. 1974; Marcus and Fuller 1989). In turn, some reef demersal hypoplankton spend much of their lives in the waters above the reef. These categories are limited and do not reflect the true ecological position of the zooplankton.

In addition, the paucity of published information on gelatinous zooplankton in the study area does not mean that they are absent. Instead, it is because gelatinous zooplankton are fragile and generally larger than most other plankton that they are excluded from typical plankton studies. For these reasons, few quantitative data are available from oceanic and shelf waters. However, the major nearshore gelatinous groups appear to be the ctenophores and medusae. These groups, while generally found in low numbers in Florida estuaries (Hopkins 1966, 1977; Squires 1984; Brand 1988), can be seasonally abundant (Reeve and Baker 1975). In addition, ctenophores and medusae are major predators of other zooplankton (Bishop 1967; Cargo and Schultz 1967; Miller and Williams 1972; Clifford and Cargo 1978; Reeve et al. 1978). Therefore, gelatinous zooplankton should be given as much attention as other, better sampled zooplankton taxa.

Oceanic Waters

There are several reports covering the zooplankton of the Loop and Florida Currents (Owre and Foyo 1967; Michel et al. 1976; Stepien 1980). However, most of the quantitative data come from eastern Gulf (27°N, 86°W) studies by Hopkins (1982) and Hopkins et al. (1981), and are therefore representative of the oligotrophic tropical/subtropical oceanic province. The study area's oceanic zooplankton community, similar to other oceanic tropical/subtropical systems, is very diverse (Hopkins et al. 1981) and low in biomass (Hopkins 1982; Lancraft et al. 1988). Most zooplankton biomass is found in the mixed, upper 200 m epipelagic zone, with highest concentrations in the upper 50 m above the thermocline (Hopkins 1982). Loop Transition Water has higher biomass values (Khromov 1965; Bogdanov et al. 1968) than the Loop Current core, but still only averages 1.2 g dry wt/m^2 in the upper 1,000 m (Hopkins 1982). This value is typical of other oligotrophic oceanic boundary areas (Hopkins 1982). Zooplankton dry biomass from the Loop Transition Water for the upper 200 m (0.7 g/m^2, Hopkins 1982) is much less than that from eutrophic waters such as those off southern California (2.9 to 10.7 g/m^2; Longhurst 1967; Smith 1971) and off western Africa (6.6 g/m^2, Yashnov 1962).

Holoplankton. Hopkins' (1982) eastern Gulf of Mexico data show that the oceanic zooplankton community is dominated by holoplanktonic calanoid copepods which make up more than 80% by number, and about 50% by biomass. The four largest contributors of copepod biomass are *Clausocalanus*, *Euchaeta*, *Pleuromamma*, and *Eucalanus* (Hopkins 1982), and combined, they contribute almost half (47%) of the copepod biomass in the upper 1,000 m. The first two genera were also considered important in surveys of Southeast Florida oceanic waters (Bowman 1971) as well as of adjacent waters to the south (Michel et al. 1976).

Euphausiids and chaetognaths are second and third, respectively, in biomass contribution. Each contributes about 10% of total zooplankton biomass (Hopkins 1982). Important euphausiid genera include *Euphausia* and *Stylocheiron*, which contribute 79% of all euphausiid biomass. The most abundant oceanic chaetognath species is *Sagitta enflata* (Michel 1984). *Lucifer faxoni* is the most important planktonic decapod, comprising 2% of total zooplankton biomass.

Oceanic zooplankton biomass decreases with depth but varies during the diel period--a result of strong diel vertical migration in many species (**Table 6.2**). For example, *Euphausia* is a dominant in the upper 30 m at night but not during the day. Zooplankton biomass (day and night) is most concentrated in the upper 50 m, with an average of 59% of total biomass residing in the upper 200 m (Hopkins 1982).

Meroplankton. Meroplanktonic forms such as decapod and mollusc larvae are relatively scarce in the oceanic province (Hopkins unpubl. data), becoming more important towards shore. Consequently, meroplanktonic species will be more prominently discussed in the shelf section.

Shelf Waters

Despite considerable information on Florida shelf communities to the north and east, little is known about the zooplankton of the study area (King 1949; Davis 1950; Tabb et al. 1962). However, much of the zooplankton community structure of the Southwest Florida shelf can be inferred from other studies. The Southwest Florida shelf zooplankton community is a mixture of shallow-dwelling, oceanic fauna, in addition to some neritic forms (King 1949; Davis 1950; Turner et al. 1979; Hopkins et al. 1981) and

Table 6.2. Comparisons of principal genera (biomass >5% of total) in various depth zones in the eastern Gulf of Mexico by day and night (From: Hopkins 1982).

Depth Zone (m)	Day	Night
0-30	*Clausocalanus* (25.8)* *Sagitta* (10.1)	*Clausocalanus* (21.9) *Euphausia* (41.0)
30-100	*Euchaeta* (30.8) *Sagitta* (23.1)	*Clausocalanus* (39.2) *Sagitta* (39.0) *Stylocheiron* (37.2) *Euchaeta* (21.3) *Pleuromamma* (18.2)
100-200	*Sagitta* (30.5) *Pleuromamma* (6.8)	*Sagitta* (31.2) *Pleuromamma* (19.8) *Stylocheiron* (18.8) *Euphausia* (11.4)
200-500	*Pleuromamma* (70.9) *Euphausia* (63.7) *Sagitta* (40.4)	*Sagitta* (41.0) *Pleuromamma* (18.5) *Eucalanus* (8.6)
500-800	*Eucalanus* (46.7) *Pleuromamma* (12.6) *Sagitta* (9.5)	*Eucalanus* (49.2) *Sagitta* (8.4) *Pleuromamma* (6.8)
800-1,000	*Eucalanus* (20.1) *Sagitta* (3.6)	*Eucalanus* (19.4) *Sagitta* (2.7)

* Numbers in parentheses are integrated dry wt biomass values (mg/m^2).

meroplanktonic larvae. As the section on Hydrographic Conditions implies, circulation patterns exist that can transport epipelagic oceanic species onto the shelf as well as move neritic species offshore (Stepien 1980). In Florida shelf systems, diversity tends to decrease and abundance to increase shoreward (Hopkins 1966; Bowman 1971). Diversity decreases on the shelf because many of the deeper-dwelling (mesopelagic) zooplankton species, which nocturnally migrate into near-surface layers, disappear in the shallower shelf waters (Hopkins et al. 1981).

Holoplankton. Epipelagic oceanic copepod species such as *Arcocalanus longicornis*, *Corycaeus speciosus*, *Temora turbinata*, and *Undinula vulgaris*, along with other shallow living species (**Table 6.3**), are sometimes found in shelf waters <50 m deep, far landward of their typical habitat (Hopkins et al. 1981). Epipelagic euphausiids (i.e., *Euphausia tenera* and *Stylocheiron carinatum*) and the decapod *Lucifer faxoni* mimic the copepod pattern. As previously mentioned, this pattern is expressed because the above species do not migrate below 50 m, even in the open ocean, and therefore can survive in the shallow shelf waters.

Resident shelf species, those distributed predominantly over the shelf, are members of the calanoid copepod genera *Centropages* (*C. furcatus*, *C. velificatus*, and *C. violaceus*), *Eucalanus* (*E. pileatus*), *Labidocera* (*L. aestiva*), and *Paracalanus* (*P. quasimodo*) (Bowman 1971; Hopkins 1982; Squires 1984). The chaetognath *Sagitta helenae* is also considered a shelf species (Pierce 1954).

Table 6.3. Important holoplanktonic copepod species in five hydrographical regions of the eastern Gulf of Mexico (From: Hopkins 1977, 1982; Hopkins et al. 1981; Turner and Hopkins 1985).

OCEANIC

Paracandacia bispinosa (30/30)*
Pleuromamma abdominalis (50/S)†
Haloptilus longicornis (50/50)
Scolecithrix bradyi (50/50)
Pleuromamma gracilis (100/30)
Chirundina streetsi 100/60)
Corycaeus furcifer (100/100)
Candacia varicans (100/100)
Pleuromamma xiphias (150/50)
Pleuromamma piseki (300/15)
Euchaeta media (200/50)
Gaetanus miles (200/210)
Euchirella splendens (200/550)
Undeuchaeta plumosa (300/15)
Candacia paenelongimana (300/50)
Euchirella messinensis (300/100)
Gaetanus minor (350/100)
Undeuchaeta major (400/350)

OCEANIC/SHELF

Clausocalanus furcatus (S/S)
Pontella spinipes (S/S)
Labidocera acutifrons (S/S)
Arcocalanus longicornis (S/S)
Corycaeus speciosus (S/S)
Farranula gracilis (S/S)
Centropages violaceus (S/S)
Macrosetella gracilis (S/S)
Miracia efferata (S/S)
Pontella plumata (S/S)
Temora stylifera (S/S)
Undinula vulgaris (S/S)
Microsetella rosea (S/S)
Calocalanus pavo (S/S)
Oithona plumifera (S/S)
Nannocalanus minor (S/S)
Paracalanus aculeatus (S/S)
Temora turbinata (15/S)
Candacia curta (15/S)

OCEANIC/SHELF (continued)

Scolecithrix danae (15/S)
Copilia mirabilis (15/S)
Candacia pachydactyla (15/S)
Eucalanus subtenuis (15/S)
Euchaeta marina (15/S)
Macrosetella oculata (15/S)
Eucalanus monachus (15/S)
Corycaeus lautus (15/15)
Paracandacia simplex (30/30)
Acartia danae (50/S)
Eucalanus sewelli (50/S)
Lucicutia flavicornis (50/S)
Neocalanus gracilis (50/S)
Rhinocalanus cornutus (50/S)
Calanus tenuicornis (50/50)
Euchaeta paraconcinna (50/50)
Euaetideus acutus (100/60)
Candacia bipinnata (135/75)
Eucalanus hyalinus (400/100)

SHELF

Eucalanus pileatus (S/S)
Paracalanus quasimodo (S/S)

SHELF/ESTUARY

Labidocera aestiva (S/S)
Oithona nana (S/S)
Oithona simplex (S/S)
Centropages hamatus (S/S)

ESTUARY

Acartia tonsa (S/S)
Parvocalanus crassirostris (S/S)
Oithona colcarva (S/S)
Pseudodiaptomus caronatus (S/S)

* Numbers in parentheses are depths (m) of peak abundance (day/night).
† S = surface.

Meroplankton. Shelf meroplankton are important because many of the young of commercial species are in this grouping. Zooplanktonic larvae of the pink shrimp *Penaeus duorarum*, rock shrimp *Sicyonia brevirostris*, spiny lobster *Panulirus argus*, stone crab *Menippe mercenaria*, blue crab *Callinectes sapidus*, calico scallop *Argopecten gibbus*, and the brief squid *Lolliguncula brevis* are found in waters of Florida Bay and the Florida Keys (Tabb et al. 1962; Ingle et al. 1963; Cobb et al. 1973; Lindall et al. 1973; Sullivan 1979). The larvae of the pink shrimp, in particular, can make up over 90% by number of the planktonic commercial invertebrates (Lindall et al. 1973).

Nearshore Waters (Estuaries)

As was the case for the shelf area, information on estuarine fauna in the study area is scarce. Estuarine zooplankton tend to be distinct from oceanic and shelf communities, as would be predicted by the extreme hydrographic variability characteristic of these habitats. Holoplanktonic forms are still most important but meroplanktonic forms are much more important than in oceanic and shelf areas (Kelly and Dragovich 1967; Hopkins 1977). In general, cyclopoid copepods replace calanoid copepods as the numerically dominant taxa, with the larger calanoid copepods being more important in terms of biomass (Hopkins 1977; Squires 1984).

Species composition in estuaries is often a function of salinity. For example, species associated with higher salinities (*Labidocera aestiva*, *Oithona nana*, *Paracalanus quasimodo*, *Parvocalanus crassirostris*, and *Temora turbinata*) will penetrate further up an estuary in dry periods. Low-salinity species such as *Acartia tonsa* and *Oithona colcarva* will be flushed towards the mouth of the estuary during wet periods (Reeve 1970; Squires 1984).

Holoplankton. *Acartia tonsa*, *Parvocalanus crassirostris*, and species of *Oithona* (*O. colcarva* and *O. nana*) are the major indigenous holoplanktonic copepod species both to the north of the study area in Tampa Bay (Hopkins 1977) and Charlotte Harbor (Squires 1984), and to the north and east in Biscayne Bay (Woodmansee 1958; Reeve 1964, 1970). These four copepod species, along with an appendicularian (*Oikopleura dioica*), represent about 40 and 60% of total zooplankton in terms of numbers and biomass, respectively, for West Florida estuaries (Hopkins 1977; Squires 1984). *Labidocera aestiva* is also a very common estuarine species found on both sides of the study area (Woodmansee 1958; Hopkins 1977; Squires 1984). The chaetognaths *Sagitta hispida* and *S. tenuis* are also characteristic components of zooplankton communities in Florida estuaries (Pierce 1951, 1954; Squires 1984; Turner and Hopkins 1985).

Meroplankton. Meroplanktonic shelf species, particularly the pink shrimp *Penaeus duorarum*, can occur in great numbers in Florida Bay, as has already been stated. However, typically dominant estuarine meroplankton include mostly benthic larvae from cirripedes, echinoderms, gastropods, pelecypods, and polychaetes (Woodmansee 1958; Reeve 1964, 1970; Hopkins 1977; Squires 1984). These forms represent about 10 to 20% of total zooplankton biomass.

Tychoplankton/Hypoplankton. Tychoplankton and hypoplankton are rarely abundant (Hopkins 1977; Squires 1984) and those most frequently seen are cumaceans, gammarid amphipods, harpacticoid copepods, nematodes, ostracods, platyhelminth worms, and small isopods.

Nearshore Waters (Coral Reefs)

Coral reef zooplankton communities are characterized by high abundance and diversity (Johansson 1984). The reef is an area of heightened productivity overlain by oceanic/shelf waters generally much lower in productivity. Reef species composition (a mixture of oceanic/shelf and resident reef species) is reflected in this hydrographic setting. Summarizing data mostly from Indo-Pacific reefs, Porter et al. (1978) estimated that resident demersal zooplankton (hypoplankton) provide about 75% of the zooplankton biomass. Therefore, local hypoplankton are generally much more important than pelagic oceanic species in reef zooplankton communities (Johansson 1984).

Holoplankton. The zooplankton community of Alligator Reef (Florida Keys) is dominated by copepods (Emery 1968; Cahoon and Tronzo 1988). However, most of these are demersal or epibenthic harpacticoid copepods, which will be treated in the hypoplankton section. Of the truly planktonic copepods, the most abundant taxa are common estuarine species, including *Acartia tonsa*, *A. spinata*, *Oithona nana*, and *O. oculata*. Among the chaetognaths, the oceanic *Sagitta enflata* is the most common species in the reef community, although a few nearshore *S. hispida* have also been collected. Larvaceans, principally *Oikopleura* sp., are also found in substantial numbers above the reef.

Meroplankton. Emery (1968) and Cahoon and Tronzo (1988) both collected small numbers of larval forms of inshore animals at Alligator Reef. These organisms included fish, shrimp, and crab larvae.

Tychoplankton/Hypoplankton. Emery (1968) and Cahoon and Tronzo (1988) have shown that demersal zooplankton dominate the reef zooplankton community of Alligator Reef, especially during the night when most groups migrate into the water column. The dominant hypoplanktonic taxa are harpacticoid copepods, followed by nematodes, mysids, ostracods, polychaetes, amphipods (both caprellid and gammarid), and cumaceans. The mysids, including *Mysidium gracile*, *M. integrum*, and *M. columbrae*, are the only hypoplankton species listed. Unfortunately, neither of the above papers identified the other groups to the species level, so discussion of species composition is impossible. However, from the data presented in the above and other papers (see Cahoon and Tronzo 1988 for review), it can be concluded that all the major reef zooplankton groups are dependent on the benthic reef environs, particularly the sandy regions, for their primary habitat.

Seasonal Trends in Abundance and Biomass

Oceanic/Shelf Waters

Evidence for a distinct seasonal pattern of zooplankton biomass in the oceanic and shelf areas is weak. Information from one eastern Gulf of Mexico oceanic station indicates that total biomass varies little (maximum is slightly over twice the minimum) (Lancraft et al. 1988), with the maxima occurring during periods of greatest Loop Current intrusion on the station. This is no greater than the variability induced by mesoscale patchiness in low-latitude, oligotrophic gyre systems (Haywood 1986).

Population peaks of shelf-break zooplankton species appeared throughout the year (Flock and Hopkins 1981), with most peaks in June. However, like the oceanic area, peaks in biomass were only two to three times the minima. Most likely, these patterns indicate a general dampened seasonality modified by Loop Current generated pulses of higher productivity both in Transition Waters of the eastern Gulf of Mexico and over the shelf.

Nearshore Waters

While there are limited qualitative data for the zooplankton communities in the study area, there are no quantitative seasonal data on species other than those of some commercial importance. However, a pattern of multiple zooplankton population peaks, produced by individual species sequentially throughout the year, was observed by investigators from areas adjacent to the study area (Reeve 1964, 1970; Squires 1984). Overall biomass values tended to rise in the summer/fall months--a trend that some (Woodmansee 1958; Reeve 1964) attributed to increased rainfall during those months. Biomass maxima were generally two to six times minima and were scattered throughout the year (Reeve 1970; Squires 1984). Additionally, the above workers found no wintertime reduction of estuarine zooplankton biomass typical of more northern Florida bays (Hopkins 1977). It is likely that these patterns occur in Florida Bay and other estuaries in the study area.

Conclusions

Without a good data base on community structure, the environmental consequences of any human activity in the shelf and nearshore regions cannot be accurately predicted. However, certain relevant observations can be made using information from other zooplankton investigations. In the oceanic region of the study area, currents can be rapid and of considerable geographic extent, resulting in rapid exchange of massive volumes. The zooplankton community, then, will have new immigrants advected from the Loop Current or resident eastern Gulf waters, allowing relatively rapid replacement of lost members of the population. Zooplankton generation times are short (one to two months), so reproductive replacement will also proceed relatively rapidly. Also, the geographic distribution of oceanic species tends to be extensive, so it is unlikely that a significant fraction of a population would be affected by an oil spill. Therefore, an anthropogenic disturbance would probably have only slight-to-moderate direct effects on the oceanic zooplankton community.

In the shelf, estuarine, and coral reef regions, there may be more extensive consequences of an anthropogenic disturbance. In these habitats, meroplankton, particularly the larvae of commercially important species, are more abundant. Additionally, important shelf and estuarine species have eggs and young associated with the bottom, making them especially vulnerable to concentrations of chemicals in or near the bottom sediment. Likewise, the dominant zooplankton in coral reefs are demersal or epibenthic and therefore also highly susceptible to environmental disturbance. The more refractory components of oil from an oil spill could continue to coat bottom sediments for periods up to years (E. Van Vleet, pers. comm. 1989, Univ. of South Florida), thereby increasing the necessary time required for ecological recuperation in these areas. Damage to zooplankton, *per se*, may be a moot point in sensitive nearshore areas because oil concentrations necessary to kill the zooplankton probably would destroy the other major elements (e.g., the benthos) of the ecosystem as well.

Surprisingly, much more is known about the community structure and dynamics of offshore zooplankton than is known about the closer shelf and estuarine systems. The real and obvious data gap in this field is simply the lack of any basic quantitative surveys of species composition and estimates of population sizes. Data such as these are crucial in attempts to characterize the zooplankton community in the study area. Seasonal studies of ecological, physiological, and physical parameters are necessary to understand trends in productivity and seasonal population dynamics of zooplankton from the shelf, estuarine, and coral reef areas. Florida Bay zooplankton dynamics, particularly near shore, are further complicated by irregular (human-induced) runoff patterns from the Everglades.

Basic data on zooplankton species composition, abundance, and distribution in the study area, especially in the shelf and nearshore (estuarine and coral reef) regions, could be obtained through systematic, seasonal surveys. These surveys should be coupled with seasonal hydrographic studies, in order to evaluate the effect of hydrographic dynamics (e.g., horizontal advection) on zooplankton distribution and abundance. This would give some idea of the residence and transport times of populations in areas potentially affected by human activities in the marine environment. Over the longer term, culturing experiments could be conducted to estimate growth and reproduction capabilities. This information is difficult to obtain from the literature, as little is known of subtropical zooplankton generation times. Generation times could be used, along with horizontal transport estimates, to assess recuperation potential.

Research needs in the study area, ultimately, would be those perceived by the funding agency. The effect of an oil spill, for example, on benthic-associated species and meroplanktonic larvae would certainly need to be addressed. If impact on zooplankton abundance, *per se*, is the primary concern, then given what has been stated above regarding relatively quick replacement and recuperation times, at least for the oceanic/shelf species, perhaps little needs to be done. However, if there is an attempt to examine the structure and dynamics of the entire ecosystem in the study area, then zooplankton, in their functional roles as prey and predators, are as important as any other community component and deserve their share of attention.

ICHTHYOPLANKTON

Thomas L. Hopkins

Three main horizontal zones of ichthyoplankton distribution are defined for the study area, based on the primary location of adult spawning activity and concentration of larvae: (1) Oceanic--water depth >200 m; (2) Shelf--water depth <200 m, exclusive of Florida Bay; and (3) Estuarine--Florida Bay, Everglades National Park drainages, and Naples Bay. Within the shelf zone, there are three general patterns of ichthyoplankton distribution: (a) Widespread--larvae abundant across most of the shelf; (b) Outer Shelf--larvae most abundant between the 50- and 200-m depth contours; and (c) Inner Shelf--larvae concentrated inshore of the 50-m depth contour.

Vertical distribution patterns cannot be precisely assessed, as most ichthyoplankton collections were obtained by oblique sweeps of bongo nets over a wide range of depths. Generalized vertical profiles for certain taxa (e.g., Myctophidae [lanternfishes]) may be outlined using data from outside the study area. Neuston nets were also employed in most studies, and data on certain taxa indicate higher numbers of individuals in these surface samplers, which will be noted where applicable.

Taxonomic Dominants

The term "indicator species" is used primarily to describe species that dominate ichthyoplankton collections at certain times or within certain locations. For commercially important species (see below), a species may be included as an indicator if it is characteristic of a region, or a particular time of year, even though its overall abundance may be low (e.g., *Megalops atlanticus* [tarpon]; Eldred 1967a, 1972).

Information regarding the ecology of ichthyoplankton species and assemblages in the study area is virtually non-existent. For this reason, and because it is logical to assume that effects of human development will be measured in economic terms, indicator species for each of the distribution zones are divided into three categories based on their direct importance to humans: (a) Commercially Important--species or taxa for

which there is an active commercial or recreational fishery in the State of Florida, although not necessarily within the study area; (b) Potentially Commercially Important--species or taxa for which a fishery is currently being, or may eventually be, considered. In this case, fisheries for the taxa may be ongoing or have been suggested outside the State of Florida; and (c) Commercially Unimportant--No fishery activities or any suggestion thereof anywhere.

Oceanic Waters

Ichthyoplankton of the oceanic region of the southeastern Gulf of Mexico have been inadequately studied. Most published information is from a few collections reported by Houde et al. (1979) and Richards (1984). The most comprehensive ichthyoplankton data for the oceanic Gulf of Mexico are available from the SouthEast Area Monitoring and Assessment Program (SEAMAP); however, only a few oceanic groups (i.e., coryphaenids, scombrids, and xiphiids) have been analyzed, and those only from the earliest collections in 1982 and 1983 (Richards et al. 1984; Kelley et al. 1985). Unpublished, qualitative data (i.e., dominance by frequency of occurrence and total number collected) have also been obtained from the SEAMAP data base for several oceanic families.

Commercially Important Taxa. Scombrid (mackerel and tuna) larvae dominate the open ocean commercially important taxa, but only a few of the tuna species (family Scombridae) have been collected in any numbers. Available data suggest that in the study area, the fish most often collected are mackerels (*Auxis* spp.), little tunny (*Euthynnus alletteratus*), blackfin tuna (*Thunnus atlanticus*), and bluefin tuna (*T. thynnus*), although there is a strong seasonal component and interannual variability is high (Houde et al. 1979; Richards 1984; Richards et al. 1984; Kelley et al. 1985; McGowan and Richards 1986).

Overall, the abundance of this family is low, but recent evidence suggests that scombrid larvae may be concentrated along frontal zones such as the Loop Current (W. J. Richards, pers. comm. 1989, NMFS, Miami, FL) or the Mississippi River plume in the northern Gulf (Grimes et al. 1987) and so be greatly underestimated by the broad scale surveys such as those cited above.

Other commercially important families with earliest larval stages in oceanic waters are the Albulidae (bonefishes) (Eldred 1967b); Coryphaenidae (dolphins) (Richards et al. 1984; Kelley et al. 1985); Elopidae (tarpons) (Eldred and Lyons 1966; Eldred 1967a, 1972; Smith 1980); Istiophoridae (billfishes) (Richards et al. 1984; Kelley et al. 1985); and Xiphiidae (swordfishes) (Grall et al. 1983). None of these families show high intra-annual abundances but all are of considerable importance to commercial and recreational fishing interests and are characteristic of open ocean waters. Low abundances may be due in part to aggregation along frontal zones and to concentration in the neustonic layer.

Potentially Commercially Important Taxa. This group comprises two families: Myctophidae (lanternfishes) and Gonostomatidae (lightfishes). Both overwhelmingly dominate ichthyoplankton collections in oceanic waters, and in fact do so in virtually all oceanic regions of the world.

Predominant in this group is the family Myctophidae. This family generally ranks in the top five in both frequency of occurrence and abundance in ichthyoplankton collections (Houde et al. 1979; Richards 1984; Kelley et al. 1985), but if inshore and shelf groups are removed from consideration, it ranks first in both categories. Species which dominate both the ichthyoplankton and adult collections include *Ceratoscopelus* species

(cf. *warmingii/townsendi*), *Benthosema suborbitale*, *Myctophum affine/nitidulum*, and *Notolychnus valdiviae* (Houde et al. 1979; Richards 1984). These four species account for up to 60% of the adult myctophid community of the eastern Gulf (Gartner et al. 1987), with an estimated nighttime biomass in the epipelagic zone of 639 kg wet wt/km^2 (Hopkins and Lancraft 1984).

Second only to myctophids in abundance but exceeding them in biomass (679 kg wet wt/km^2, Hopkins and Lancraft 1984) is the family Gonostomatidae. Dominant members of this family in the ichthyoplankton include *Gonostoma elongatum* and the *Cyclothone* species complex. Several other abundant species which were originally placed in the family Gonostomatidae and are now separated are *Vinciguerria nimbaria* (Photichthyidae) and *Maurolicus muelleri* (Sternoptychidae), *M. muelleri* being especially abundant in ichthyoplankton collections. Houde et al. (1979) reported from that abundances of larval *M. muelleri* ranged from 1 to 54.7 individuals under 10 m^2 throughout the eastern Gulf study area, whereas abundances of the other species mentioned above ranged from 0.1 to 9 individuals under 10 m^2.

Adult myctophids and gonostomatids have been often mentioned as targets for potential fishery exploitation in various parts of the world, and active or exploratory fisheries are currently underway for several myctophid species (see Gjosaeter and Kawaguchi 1980 for review). Vertical distributions of larvae of both these families are similar, with most larvae concentrated within the upper 150 m. Myctophid larvae show discrete patterns of vertical zonation, by species or species complex (Loeb 1980, in the Pacific Ocean; W. J. Conley, unpubl. data 1989 [for the eastern Gulf of Mexico], Dept. Mar. Sci., Univ. of South Florida, St. Petersburg). Vertical data for *G. elongatum* larvae indicate that none are found shallower than 25 m (Lancraft et al. 1988).

Commercially Unimportant Taxa. The only truly oceanic group in this category is the family Exocoetidae (flyingfishes). Richards (1984) noted that the abundances of larvae of this group can be poorly represented in offshore collections because they are confined to the neuston layer. When a neuston net is employed, both their frequency of occurrence and abundance can be relatively high (Kelley et al. 1985).

Shelf Waters

All published information on ichthyoplankton collections from shelf waters of the study area comes from Houde and his colleagues and students (Houde and Chitty 1976; Houde et al. 1976, 1979; Houde 1977a,b,c; Dowd 1978; Leak 1981; Houde 1982). The most comprehensive of these works is Houde et al. (1979) in which virtually all of the material from these other reports is incorporated. All of these reports are based on 17 ichthyoplankton surveys conducted between 1971 and 1974 over the entire West Florida continental shelf and offshore areas using 61-cm bongo nets.

Commercially Important Taxa. One of the most abundant larvae is the carangid *Decapterus punctatus* (round scad), which is broadly distributed across the shelf (though somewhat more abundant on the inner shelf). Larvae of this species are found throughout the year, and seem to be concentrated in the study area during winter (Leak 1981; J. Ditty, pers. comm. 1989, Center for Wetland Resources, Louisiana State Univ., Baton Rouge). Abundance and standing stock estimates over the entire West Florida shelf for 1971 to 1974 are 1.8 to 53.0 larvae under 10 m^2 and 10.6 to 416.5 x 10^9 larvae, respectively (Leak 1981).

Outer shelf species considered to be commercially important are the carangid *Trachurus lathami* (rough scad) and the mugilid *Mugil cephalus* (striped mullet). Both of these show highest abundances in fall and winter; neither spawn in summer. Estimated

mean annual abundance of *T. lathami* over the entire West Florida shelf between 1971 to 1974 was 14.3 x 10^9 larvae (Leak 1981). *Mugil cephalus* abundances were not calculated by Houde et al. (1979) because relatively few larvae were captured. Larvae of this species are virtually restricted to surface waters (Richards 1984) and spawning appears to occur near the shelf edge, thus actual abundance was probably greatly underestimated by Houde et al. (1979).

Inner shelf indicator species include the clupeids *Sardinella anchovia* (Spanish sardine; same as *S. aurita* of recent literature) and *Opisthonema oglinum* (Atlantic thread herring), and the carangid *Chloroscombrus chrysurus* (Atlantic bumper). All of these are components of the burgeoning "baitfish" fishery in Florida (Houde et al. 1979; Collins and Finucane 1984). Houde et al. (1979) reported weighted mean abundances of larvae under 10 m^2 for these species to be 31.0, 30.5, and 1.7, respectively, over the Southwest Florida shelf.

Potentially Commercially Important Taxa. There are no known species in this category over the shelf in the study area.

Commercially Unimportant Taxa. Three species of bothid flatfishes--*Bothus robinsi* (twospot flounder), *Etropus rimosus* (gray flounder), and *Syacium papillosum* (dusky flounder)--and one species of sea bass (*Diplectrum formosum*, sand perch) are highly abundant across the shelf in the study area. Houde et al. (1979) found that the larvae of all four species occurred throughout the year, although seasonal variations were observed, and all were among the 20 most abundant species collected. Weighted mean abundances for these species were 12.3, 3.4, 17.1, and 9.8 larvae under 10 m^2 over the Southwest Florida shelf. The larvae of *D. formosum* accounted for 56% of all serranid larvae collected (Houde 1982).

The haemulid *Orthopristis chrysoptera* (pigfish) and the bothid *Citharichthys macrops* (spotted whiff) are important inshore components of the shelf ichthyoplankton (Dowd 1978; Houde et al. 1979; Collins and Finucane 1984). Collins and Finucane (1984) found *O. chrysoptera* to be an important component of the ichthyoplankton inshore of the 10-m isobath during winter. *C. macrops* was the 16th most abundant species collected by Houde et al. (1979), with a weighted mean abundance of 1.3 larvae under 10 m^2.

Two other species of *Citharichthys--C. cornutus* (horned whiff) and *C. gymnorhinus* (anglefin whiff)--are important components of the outer shelf ichthyoplankton, with the former more abundant and generally found farther offshore than the latter (Dowd 1978; Houde et al. 1979). Weighted mean abundances for *C. cornutus*, which was the 15th most abundant species collected by Houde et al. (1979), was estimated at 3.9 larvae under 10 m^2.

The family Bregmacerotidae (codlets), the species of which are oceanic as adults, include two species whose larvae are abundant over the outer shelf. These are *Bregmaceros cantori* (= *Bregmaceros* Type B; Houde et al. 1979; Milliken and Houde 1984), which is the predominant species, and *B. houdei* (= *Bregmaceros* Type A; Houde et al. 1979; Saksena and Richards 1986). Weighted mean abundances of *B. cantori*, which was the seventh most abundant species collected by Houde et al. (1979), was calculated at 15.6 larvae under 10 m^2 over the Southwest Florida shelf (Houde 1981). Most larvae were collected in waters deeper than 50 m, but a number of captures were recorded inshore to 30 m depth. Extension of the larvae of this oceanic species into relatively shallow waters was also noted by Richards (1984). *Bregmaceros houdei* was 12th in overall abundance of Florida shelf ichthyoplankton species with 7.9 larvae under

10 m^2 (Houde et al. 1979), most of which were captured offshore of the 100-m depth contour (Houde 1981).

Nearshore Waters

There are few reports dealing with ichthyoplankton assemblages within estuarine habitats in the study area, and these are scattered over the range of estuarine systems: Naples Bay (Dohner 1987); Everglades National Park (Jannke 1971; Collins and Finucane 1984); and Florida Bay (Powell et al. 1987, 1989). Of these, Dohner (1987) and Powell et al. (1989) are the most comprehensive treatments, however, Powell et al. (1989) identified only a few taxa below the family level. Jannke's (1971) research dealt solely with sciaenid larvae and seasonality of spawning and did not provide relative abundances of individual species.

Commercially Important Taxa. Three commercially important families are dominant elements of the estuarine ichthyoplankton: Engraulidae (anchovies), Clupeidae (herrings), and Sciaenidae (drums). The family Engraulidae is important in inshore (<10 m depth) and estuarine waters, especially during summer months (Collins and Finucane 1984; Dohner 1987; Powell et al. 1989). Dohner (1987) found that in Naples Bay, larval *Anchoa mitchilli* (bay anchovy) was more abundant in the upper (lower salinity) portion of the estuary, whereas the larvae of *A. hepsetus* (striped anchovy) predominated in the lower estuary. Together, these two species accounted for 41% of all ichthyoplankton collected in Naples Bay.

In the family Clupeidae, *Brevoortia* spp. (menhaden) and *Opisthonema oglinum* (Atlantic thread herring) are also important at different times of the year, the former in winter, the latter in summer (Collins and Finucane 1984; Dohner 1987). Both species appear to spawn mainly in inshore waters <10 m deep for *Brevoortia* spp. and <30 m deep for *O. oglinum* (Collins and Finucane 1984). After spawning, larvae apparently move or are carried into estuarine nursery grounds.

The value of these two taxa as estuarine indicators is uncertain. Collins and Finucane (1984) found few larvae of *Brevoortia* spp. and no *O. oglinum* within the estuaries sampled; all occurrences were at the mouth of the estuary and farther offshore along the Florida Everglades. In contrast, Dohner (1987) found significant numbers of larvae of *Brevoortia* spp. throughout Naples Bay during winter and of *O. oglinum* in the middle and lower portions of the bay during summer.

Many species of the family Sciaenidae, especially *Cynoscion* spp., use estuarine waters as nursery grounds. Dohner (1987) reported *C. arenarius* (sand seatrout) to be abundant in mid-bay waters, where larvae are found throughout the year; but peak abundances occurred between March and October. Powell et al. (1989) found the congener *C. nebulosus* (spotted seatrout) to be the most abundant sciaenid in the Florida Bay system, occurring in all seasons except winter, with a peak abundance in late spring. This species was more abundant in the western than the eastern bay (Rutherford et al. 1989). Collins and Finucane (1984) reported few sciaenids in their collections. This appears to be due to sampling limitations; Collins and Finucane (1984) sampled only at the surface, whereas Dohner (1987) and Powell et al. (1989) both reported maximum catches of *Cynoscion* in subsurface or bottom samples. There are some data to suggest that pre-flexion *C. arenarius* perform diel vertical migrations to maintain their position within the estuary (Peebles 1987).

Potentially Commercially Important Taxa. There are no known species in this category over the shelf in the study area.

Commercially Unimportant Taxa. Gobiid (goby) larvae are extremely abundant in estuarine waters, generally ranking first or second in overall abundance (Collins and Finucane 1984; Dohner 1987; Powell et al. 1989). However, this family is also an abundant component of shelf and oceanic ichthyoplankton (Houde et al. 1979; Richards 1984). This fact, coupled with the taxonomic diversity of the family and difficulty in identifying lower taxa make most of the gobiids, at present, a poor taxon to use as a habitat descriptor.

A few species of gobies may currently be of some use as habitat indicators. Dohner (1987) identified three species from Naples Bay. In decreasing order of abundance, *Microgobius thalassinus* (green goby), *Gobiosoma robustum* (code goby), and *G. bosci* (naked goby) were dominant members of the bay ichthyoplankton from spring through fall. Peak abundances of the two *Gobiosoma* species were separated along the salinity gradient in much the same manner as the *Anchoa* (anchovy) species, with *G. bosci* mainly in the upper estuary and *G. robustum* in the lower. *Microgobius* spp. and *Gobiosoma* spp. were also reported as being abundant inshore (<10 m) and in the estuary (Collins and Finucane 1984). However, there could be up to four and eight species, respectively, within these two genera.

Blenniids (combtooth blennies) have been reported as abundant members of the ichthyoplankton by Dohner (1987) and Powell et al. (1989), but few specimens have been identified below family level in either study. Family diversity and lack of species level identifications again present the same difficulties in using this group as indicators.

Larvae of the sciaenid *Bairdiella chrysoura* (silver perch) are abundant in Everglades National Park and Naples Bay waters, but peak abundances appear temporally offset, with Everglades larvae being most abundant in winter (January-February, Jannke 1971) and Naples Bay larvae being most abundant in spring to early summer (April-June, Dohner 1987). *Bairdiella chrysoura* was the 12th most abundant species collected in Naples Bay (Dohner 1987).

Seasonal Trends in Abundance

Predictably, seasonal trends are most pronounced within estuarine and inshore habitats. All studies cited for shelf, inshore, and estuarine ichthyoplankton noted pronounced seasonal peaks of abundance. For some species, e.g. *Anchoa mitchilli* (bay anchovy), small larvae were present throughout the year but a pronounced peak was observed during a certain period (Dohner 1987); for others, e.g., *Chloroscombrus chrysurus* (Atlantic bumper), larvae were absent except during certain periods of the year (Houde et al. 1979; Collins and Finucane 1984).

For estuarine and inshore species, attempts have been made to correlate presence or peak abundance (= peak spawning activity) with changes in primary productivity, temperature, salinity, or a number of other biotic and abiotic factors. Variability in salinity has been shown to limit abundances and distributions of certain ichthyoplankton species within estuarine habitats (Dohner 1987; Powell et al. 1989). Houde et al. (1979) attempted to correlate surface temperature and salinity factors with larval distribution and abundance, but noted that because of the complex interrelationships of various factors and their effects on abundance, cause and effect could not be established; at best, the authors could determine a range of environmental conditions within which a given species is generally found. The overall pattern for indicator species is typically a single spawning peak, which may often be quite protracted (e.g., *Microgobius thalassinus* [green goby], Dohner 1987). There are two spawning complexes of species, one where larvae are collected in highest abundances during spring-summer and the other where larvae are mainly taken in late fall and winter.

Oceanic ichthyoplankton are variable in their response to seasonality. Epipelagic species such as scombrids appear to have spawning periods restricted to spring and summer (Houde et al. 1979; Richards et al. 1984; Kelley et al. 1985), while many of the dominant mesopelagic myctophid (lanternfish) species and *Gonostoma elongatum* (lightfish) spawn throughout the year (Lancraft et al. 1988; Gartner in prep.).

Table 6.4 lists the taxa discussed in the regional sections, along with seasonal occurrence of larvae and periods of peak abundance and (where known) temperature and salinity ranges associated with presence of the species in a given region.

Conclusions

As with zooplankton, without more accurate assessment on structure, seasonality, and environmental correlates of abundance, effects of human activities cannot be forecast with any certainty. However, it should be noted that with few exceptions, most of the indicator species described have pelagic eggs that undergo initial development in surface waters (<5 m depth). This renders them particularly vulnerable to surface disturbance. More developed but still pre-flexion larvae and especially flexion larvae of many estuarine species descend to near-bottom waters (Dohner 1987) and so are more vulnerable to bottom disturbances. It is likely, though by no means certain, that oceanic species would show less perturbation due to their generally protracted spawning seasons and broad geographic distribution of larvae (Houde et al. 1979; Gartner in prep.). In contrast, the more restricted nature of seasonal spawning and the concentration of eggs and larvae over spawning grounds and within nursery areas (e.g., Houde 1977b; Collins and Finucane 1984) probably renders nearshore and estuarine species far more sensitive to detrimental effects of human activities. Finally, it should be noted that a number of commercially important nearshore species such as *Mugil cephalus* (striped mullet), *Elops saurus* (ladyfish), *Albula vulpes* (bonefish), and *Megalops atlanticus* (tarpon) are spawned in oceanic or shelf break waters. Larvae of these species face increased natural mortality because of the long distances between natal and adult habitats, which means that they would probably be especially susceptible to deleterious environmental effects.

Within the study area, published information on ichthyoplankton assemblages is sparse. Houde et al. (1979) and Richards (1984) provide the only comprehensive oceanic data, while Houde et al. (1979) give the only overview of Southwest Florida shelf ichthyoplankton assemblages. Only two papers (Collins and Finucane 1984; Powell et al. 1989) provide broad-scale outlines of inshore and estuarine larval fish distributions in the study area. Dohner (1987) is an unpublished master's thesis.

These investigations mainly provide temporal-spatial distributional records within the study area, with only minimal correlative information between species presence (abundance) and environmental parameters. Except for Dohner (1987) and Powell et al. (1989), none of these studies use data bases compiled within the past decade. Although most of these studies have recognized and addressed the need for multi-seasonal sampling, all were relatively short-term studies (three years maximum), which do not provide sufficient data for evaluation of interannual variability.

Data comparisons among these various studies are at best approximations because of differences in sampling methodology, collection period(s), and also behavioral differences among various fish species. For example, Collins and Finucane (1984) sampled only in surface waters in shallow inshore and estuarine stations. As a result, they reported relatively few sciaenid larvae in their collections. Jannke (1971), Dohner (1987), and Powell et al. (1989) all fished both at the surface and near bottom and reported relatively abundant captures of several sciaenid species.

Table 6.4. Southwest Florida ichthyoplankton indicator species, season(s) of maximum abundance, and associated ranges of salinity and temperature in three biological provinces (Adapted from: Houde et al. 1979). See text for species references.

Species	Season(s)*	Salinity (ppt)	Temperature (°C)
OCEANIC WATERS			
Albulidae			
Albula vulpes	SU		
Coryphaenidae			
Coryphaena equisetis	SP,ESU		
C. hippurus	SP-FL		
Elopidae			
Elops saurus	Y(?)		
Megalops atlanticus	LSP,SU		
Gonostomatidae			
Gonostoma elongatum	Y		
Istiophoridae			
Istiophorus platypterus	SP,ESU		
Myctophidae			
Benthosema suborbitale	Y		
Myctophum affine†	Y(?)	31.0 - 36.9§	18.0 - 30.9
Notolychnus valdiviae	Y		
Photichthyidae			
Vinciguerria nimbaria	SP,SU		
Scombridae			
Auxis sp.	SP-FL		
Euthynnus alletteratus	SP,SU	31.0 - 36.9§	24.0 - 30.9
Thunnus atlanticus	SP,SU		
T. thynnus	SP		
Sternoptychidae			
Maurolicus muelleri	Y	31.0 - 36.9§	21.0 - 30.9
Xiphiidae			
Xiphias gladius	Y(?)		
SHELF WATERS			
Bothidae			
Bothus robinsi	SU,FL	>= 35.0	17.0 - >32.0
Citharichthys cornutus	SP,SU	>= 35.0	21.0 - 30.9
C. gymnorhinus	Y		
C. macrops	Y	33.0 - 36.9	17.0 - 30.9
Etropus rimosus	WR,SP	>= 35.0	16.0 - 30.9
Syacium papillosum	SP-FL	>= 35.0	19.0 - 32.0
Bregmacerotidae			
Bregmaceros cantori (=Type B)	Y	>= 35.0	19.0 - 31.0
B. houdei (=Type A)	Y	34.0 - 36.9	21.0 - 30.9
Carangidae			
Chloroscombrus chrysurus	SU	>= 35.0	24.0 - 31.9
Decapterus punctatus	SP,FL	>= 35.0	20.0 - >32.0
Trachurus lathami	WR,ESP		
Clupeidae			
Opisthonema oglinum	SP,SU	>= 35.0	18.0 - >31.0
Sardinella aurita (=*anchovia*)	LSU	>= 35.0	21.0 - 32.0
Haemulidae			
Orthopristis chrysoptera	WR,SP	>= 32.0	15.0 - 25.9
Mugilidae			
Mugil cephalus	WR		
Serranidae			
Diplectrum formosum	SP,SU	>= 35.0	17.0 - >32.0
ESTUARINE WATERS			
Clupeidae			
Brevoortia spp.	WR		
Opisthonema oglinum	SU		
Engraulidae			
Anchoa hepsetus	SU		
A. mitchilli	SU		
Gobiidae			
Gobiosoma bosci	SP-EFL		
G. robustus	SP-EFL		
Microgobius thalassinus	SP-FL	> 16.5	
Sciaenidae			
Bairdiella chrysoura	WR-ESU	23.5 - 37.4	16.4 - 31.8
Cynoscion arenarius	SP-FL		

* SP = Spring; SU = Summer; FL = Fall; WR = Winter; Y = Year-round; E = Early; L = Late.
† In some studies, this species is reported as *M. nitidulum*, which may be incorrect.
§ Lower salinity values reported by Houde et al. (1979) are due to a lens of fresh water overlying the sample site. It could not be determined whether larvae were actually in the lens or remained below it.

There are virtually no data on standing stock or production of ichthyoplankton in the southeastern Gulf. The estimates of Houde et al. (1979) were calculated over the entire West Florida shelf and it would be difficult to apply them confidently to the study area. However, there is a largely untapped data base available which includes long-term seasonal (spring and late summer) ichthyoplankton and hydrographic data. This is the SEAMAP data base referred to earlier.

In recent years, there has been increasing interest in the use of ichthyoplankton data to provide fishery-independent stock assessment of commercially and potentially commercially important finfish species. To this end, the SEAMAP in the Gulf of Mexico mentioned earlier was created and sampling began in 1982. Biannual (April-June and August-September) sampling began in 1984 and has continued each year, with funding continuing through at least calendar year 1990. Station locations include cross-shelf transects to 25 °N (estuarine systems excluded). Ichthyoplankton data are available, with most identifications to family and many to species level. All hydrographic data as well as ichthyoplankton samples are archived and available for use. It is therefore possible to generate a long-term, modern, broad-scale data base for ichthyoplankton in the study area. It is of paramount importance, however, that additional, short-term, fine-scale studies be undertaken as well to provide accurate determinations of species biomass and environmental correlations to abundance for ichthyoplankton within the study area.

In future plankton studies, ichthyoplankton research should be accorded a high priority, with particular attention focused on nearshore and estuarine areas. The reason is that fish larvae have much longer generation times than most zooplankton and phytoplankton species, which means a reduced capacity for rapid recovery from serious or long-term environmental disturbance. Those fish species with restricted spawning periods or areas, such as many inshore and estuarine inhabitants, would take the longest time to recuperate. Assessments of variability and periodicity of abundances of ichthyoplankton stocks of these species in the study area would allow accurate indexing and forecasting of economic loss in the event of environmental disturbance.

In the short term (one to two years), completion of baseline ichthyoplankton collections should be a priority. Broad-scale sampling of the neuston and water column for ichthyoplankton would be necessary to fill in the regional and temporal gaps left by the relatively few studies (Houde et al. 1979; SEAMAP) that have been conducted in the study area. Quarterly sampling would be the minimal acceptable sampling frequency; bimonthly would be better; and monthly over a 24-month period would be ideal. Initial baseline data are needed over the entire region. These data should be quantitative so as to provide accurate estimates of standing stock and its variation over time. In the optimal scenario, multiple discrete sample collection gear would be used to obtain vertical distribution profiles of key ichthyoplankton species. Such data would indicate zones of high abundances of various species within the water column, allowing investigators to evaluate which species would be most strongly affected during an oil spill or other environmental disturbance.

Over the longer term, data from baseline surveys could be used to pinpoint areas and periods of special interest--e.g., nursery areas, periods and depth zones of highest spawning activity and larval abundance. These could then be sampled in a more intensive manner. Physiological experiments to determine growth rates and environmental tolerances of some of the important species could also be conducted to aid in the prediction of environmental effects of human activities in the marine environment.

REFERENCES CITED

Alexander, J. E., and E. F. Corcoran. 1963. Distribution of chlorophyll in the Straits of Florida. *Limnol. Oceanogr.* 8:294-297.

Alexander, J. E., J. H. Steele, and E. F. Corcoran. 1961. The seasonal cycle of chlorophyll in the Florida Straits. In *Proc. Gulf Caribb. Fish. Inst.*, Nov. 1961, 63-67.

Austin, H. M., and J. I. Jones. 1974. Seasonal variation of physical oceanographic parameters on the Florida middle ground and their relation to zooplankton biomass on the West Florida shelf. *Fla. Sci.* 37:16-32.

Belousov, I. M., Y. A. Ivanov, S. A. Pasternak, T. S. Rass, and V. V. Rossov. 1966. Oceanographic research by the Soviet-Cuban marine expedition. *Oceanol. Acad. Sci. USSR* 6:312-320.

Bienfang, P. K., and M. Takahashi. 1983. Ultraplankton growth rates in a subtropical ecosystem. *Mar. Biol.* 76:213-218.

Bishop, J. W. 1967. Feeding rates of the ctenophore, *Mnemiopsis leidyi*. *Chesapeake Sci.* 8:259-261.

Bogdanov, D. V., V. A. Sokolov, and N. S. Khromov. 1968. Regions of high biological and commercial productivity in the Gulf of Mexico and Caribbean Sea. *Oceanology* 8:371-381.

Bowman, T. E. 1971. The distribution of calanoid copepods off the southeastern United States between Cape Hatteras and southern Florida. *Smithson. Contrib. Zool.* 96:1-58.

Brand, L. E. 1988. *Assessment of plankton resources and their environmental interaction in Biscayne Bay, Florida.* Department of Environmental Resources Management Tech. Rep. No. 88-1. Miami, FL.

Brooks, I. H., and P.P. Niiler. 1975. The Florida Current and Key West: Summer 1972. *J. Mar. Res.* 33:83-92.

Bsharah, L. 1957. Plankton of the Florida Current. V. Environmental conditions, standing crop, seasonal and diurnal changes at a station forty miles east of Miami. *Bull. Mar. Sci.* 7:201-251.

Cahoon, L. E., and C. R. Tronzo. 1988. A comparison of demersal zooplankton collected at Alligator Reef, Florida, using emergence and reentry traps. *Fish. Bull.* 86:838-845.

Cargo, D. G., and L. P. Schultz. 1967. Further observations on the biology of the sea nettle and jellyfishes in Chesapeake Bay. *Chesapeake Sci.* 8:209-220.

Carpenter, E. J. 1983. Nitrogen fixation by marine *Oscillatoria* (*Trichodesmium*) in the world's oceans. In *Nitrogen in the marine environment*, ed. E. J. Carpenter and D. C. Capone, 65-103. New York: Academic Press.

Carpenter, E. J., and J. S. Lively. 1980. Review of estimates of algal growth using ^{14}C tracer techniques. In *Primary productivity in the sea*, ed. P. G. Falkowski, 161-178. New York: Plenum Press.

Carpenter, E. J., and C. C. Price IV. 1977. Nitrogen fixation, distribution, and production of *Oscillatoria* (*Trichodesmium*) spp. in the western Sargasso and Caribbean Seas. *Limnol. Oceanogr.* 22:60-72.

Chew, F. 1955. On the offshore circulation and a convergence mechanism on the red tide region off the west coast of Florida. *Eos Trans. Am. Geophys. Union* 36:963-974.

Chew, F. 1974. The turning process in meandering currents: A case study. *J. Phys. Oceanogr.* 4:27-57.

Clifford, H. C., and D. G. Cargo. 1978. Feeding rates of the sea nettle, *Chrysaora quinquecirrha* under laboratory conditions. *Estuaries* 1:68-71.

Cobb, S. P., C. R. Futch, and D. K. Camp. 1973. The rock shrimp, *Sicyonia brevirostris* Stimpson, 1871 (Decapoda, Penaeidae). *Memoirs of the Hourglass Cruises, Vol. III, Pt. I.*

Collier, A. 1964. *Laboratory and field study of slicks produced by plankton organisms.* Interim report submitted to DDC, Washington, DC.

Collins, L. A., and J. H. Finucane. 1984. *Ichthyoplankton survey of the estuarine and inshore waters of the Florida Everglades, May 1971 to February 1972.* NOAA Tech. Rep. NMFS Circ. 6.

Corcoran, E. F., and J. E. Alexander. 1963. Nutrient, chlorophyll and primary production in the Florida Current. *Bull. Mar. Sci.* 13:527-541.

Cullen, J. J. 1982. The deep chlorophyll maximum: Comparing vertical profiles of chlorophyll *a*. *Can. J. Fish. Aquat. Sci.* 39:791-803.

Danek, L. J., and G. S. Lewbel. 1986. *Southwest Florida shelf benthic communities study. Year 5 annual report.* OCS Study MMS 86-0075. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Davis, C. C. 1950. Observations on plankton taken in marine waters off Florida in 1947 and 1948. *Q. J. Fla. Acad. Sci.* 12:67-1103.

Dohner, E. T. 1987. Ichthyoplankton distribution, abundance, and diversity of Naples Bay, Florida. M.S. thesis, Univ. of South Florida.

Dowd, C. E. 1978. Abundance and distribution of Bothidae (Pisces, Pleuronectiformes) larvae in the eastern Gulf of Mexico, 1971-72 and 1973. M.S. thesis, Univ. of Miami.

Dugdale, R. C., and J. J. Goering. 1967. Uptake of new and regenerated forms of nitrogen in primary productivity. *Limnol. Oceanogr.* 12:196-206.

Duing, W. 1975. Synoptic studies of transients in the Florida Current. *J. Mar. Res.* 33:53-73.

El-Sayed, E. S. 1972. Primary productivity and standing crop of phytoplankton. In *Chemistry, primary productivity, and benthic algae of the Gulf of Mexico, folio 22*, ed. V. C. Bushnell, 8-13. New York: American Geographical Society.

El-Sayed, E. S., and J. T. Turner. 1977. Productivity of the Antarctic and tropical/subtropical regions: A comparative study. In *Polar oceans*, ed. M. J. Dunbar, 463-503. Calgary: Arctic Institute of North America.

Eldred, B. 1967a. *Larval tarpon, Megalops atlanticus Valenciennes, (Megalopidae) in Florida waters.* Fla. Bd. Cons. Mar. Lab., Leaflet Series: Vol. IV - Immature Vertebrates, Pt. I(4).

Eldred, B. 1967b. *Larval bonefish, Albula vulpes (Linnaeus, 1758), (Albulidae).* Fla. Bd. Cons. Mar. Lab., Leaflet Series: Vol. IV - Immature Vertebrates, Pt. I(3).

Eldred, B. 1972. *Note on larval tarpon, Megalops atlanticus (Megalopidae), in the Florida Straits.* Fla. Dept. Nat. Res. Mar. Res. Lab. Leaflet Series: Vol. IV - Immature Vertebrates, Pt. I(22).

Eldred, B., and W. G. Lyons. 1966. *Larval ladyfish, Elops saurus Linnaeus 1766, (Elopidae) in Florida and adjacent waters.* Fla. Bd. Cons. Mar. Lab., Leaflet Series: Vol. IV - Immature Vertebrates, Pt. I(2).

Elmgren, R., G. A. Vargo, J. F. Grassle, J. P. Grassle, D. R. Heinle, G. Langlois, and S. L. Vargo. 1980. Trophic interactions in experimental marine ecosystems perturbed by oil. In *Microcosms in Ecological Research*, DOE Symposium Series 52, ed. J. P. Giesy, Jr., 779-800. Springfield: National Technical Information Services, U.S. Department of Energy.

Emery, A. R. 1968. Preliminary observations on coral reef plankton. *Limnol. Oceanogr.* 13:293-303.

Eppley, R. W., E. H. Renger, and W. G. Harrison. 1979. Nitrate and phytoplankton production in southern California coastal waters. *Limnol. Oceanogr.* 24:483-494.
Fanning, K. A., K. L. Carder, and P. R. Betzer. 1982. Sediment resuspension by coastal waters: A potential mechanism for nutrient re-cycling on the ocean's margins. *Deep-Sea Res.* 29:953-965.
Ferguson, R. L., and W. G. Sunda. 1984. Utilization of amino acids by planktonic marine bacteria: Importance of clean technique and low substrate additions. *Limnol. Oceanogr.* 29:258-274.
Fitzwater, S. E., G. A. Knauer, and J. H. Martin. 1982. Metal contamination and its effect on primary production measurements. *Limnol. Oceanogr.* 27:544-551.
Flock, M. E., and T. L. Hopkins. 1981. *An analysis of six groups of zooplankton in samples taken in 1978/1979 at the proposed OTEC site in the eastern Gulf of Mexico off Tampa Bay.* A report to the Lawrence Berkeley Laboratory in partial fulfillment of subcontract No. 4825302 to the Univ. of South Florida.
Gartner, J. V., Jr. In prep. *Patterns of reproduction of the dominant lanternfish species (Pisces: Myctophidae) in the eastern Gulf of Mexico.*
Gartner, J. V., Jr., T. L. Hopkins, R. C. Baird, and D. M. Milliken. 1987. The lanternfishes (Pisces: Myctophidae) of the eastern Gulf of Mexico. *Fish. Bull.* 85(1):81-98.
Gjosaeter, J., and K. Kawaguchi. 1980. *A review of the world resources of mesopelagic fish.* FAO Fish. Tech. Pap. 193.
Grall, C., D. P. deSylva, and E. D. Houde. 1983. Distribution, relative abundance, and seasonality of swordfish larvae. *Trans. Am. Fish. Soc.* 112:235-246.
Grimes, C. B., J. H. Finucane, V. M. Pettigrew, J. T. Brucks, and R. C. Herron. 1987. King mackerel early life history stages in the Gulf of Mexico: Possible association with the Mississippi River plume. Paper Presented at Florida Chapter, Amer. Fish. Soc. Annual Meeting (Abstract).
Harrison, W. G., and L. J. E. Wood. 1988. Inorganic nitrogen uptake by marine picoplankton: Evidence for size partitioning. *Limnol. Oceanogr.* 33:468-475.
Haywood, T. L. 1986. Variability in production and the role of disturbance in two pelagic ecosystems. In *Pelagic biogeography*, ed. A. C. Pierrot-Bults, 133-140. UNESCO Tech. Pap. Mar. Sci. 49.
Herbland, A., and B. Voituriez. 1979. Hydrobiological structure analysis for estimating the primary production in the tropical Atlantic Ocean. *J. Mar. Res.* 37:87-101.
Hobson, L. A., and C. J. Lorenzen. 1972. Relationships of chlorophyll maxima to density structure in the Atlantic Ocean and Gulf of Mexico. *Deep-Sea Res.* 19:297-306.
Hopkins, T. L. 1966. The plankton of the St. Andrews Bay system, Florida. *Publ. Inst. Mar. Sci.*, Univ. of Texas, 11:12-64.
Hopkins, T. L. 1977. Zooplankton distribution in surface waters of Tampa Bay, Florida. *Bull. Mar. Sci.* 27:467-478.
Hopkins, T. L. 1982. The vertical distribution of zooplankton in the eastern Gulf of Mexico. *Deep-Sea Res.* 29A:1069-1083.
Hopkins, T. L., and T. M. Lancraft. 1984. The composition and standing stock of mesopelagic micronekton at 27°N, 86°W in the eastern Gulf of Mexico. *Contrib. Mar. Sci.* 27:143-158.
Hopkins, T. L., D. M. Milliken, L. M. Bell, E. J. McMichael, J. J. Heffernan, and R. V. Cano. 1981. The landward distribution of oceanic plankton and micronekton over the West Florida continental shelf as related to their vertical distribution. *J. Plankton Res.* 3:645-658.
Houde, E. D. 1977a. Abundance and potential yield of the round herring, *Etrumeus teres*, and aspects of its early life history in the eastern Gulf of Mexico. *Fish. Bull.* 75(1):61-90.
Houde, E. D. 1977b. Abundance and potential yield of the Atlantic thread herring, *Opisthonema oglinum*, and aspects of its early life history in the eastern Gulf of Mexico. *Fish. Bull.* 75(3):493-512.
Houde, E. D. 1977c. Abundance and potential yield of the scaled sardine, *Harengula jaguana*, and aspects of its early life history in the eastern Gulf of Mexico. *Fish. Bull.* 75(3):613-628.
Houde, E. D. 1981. Distribution and abundance of four types of codlet (Pisces: Bregmacerotidae) larvae from the eastern Gulf of Mexico. *Biol. Oceanogr.* 1(1):81-104.
Houde, E. D. 1982. Kinds, distributions and abundances of sea bass larvae (Pisces: Serranidae) from the eastern Gulf of Mexico. *Bull. Mar. Sci.* 32(2):511-522.
Houde, E. D., and N. Chitty. 1976. *Seasonal abundance and distribution of zooplankton, fish eggs, and fish larvae in the eastern Gulf of Mexico.* NOAA Tech. Rep. NMFS (Spec. Sci. Rep. Fish. Ser.) 701.
Houde, E. D., S. A. Berkeley, J. J. Klinovsky, and C. E. Dowd. 1976. *Ichthyoplankton survey data report. Summary of eggs and larval data used to determine abundance of clupeid fishes in the eastern Gulf of Mexico.* Florida Sea Grant Tech. Bull. No. 32.
Houde, E. D., J. C. Leak, C. E. Dowd, S. A. Berkeley, and W. J. Richards. 1979. *Ichthyoplankton abundance and diversity in the eastern Gulf of Mexico.* New Orleans: U.S. Department of the Interior, Bureau of Land Management.
Ingle, R. M., B. Eldred, H. W. Sims, and E. E. Eldred. 1963. On the possible Caribbean origin of Florida's spiny lobster populations. *Fla. State Bd. Conserv. Tech. Ser.* 40:1-12.
Ivanov, A. I. 1966. Some data on phytoplankton of the Gulf of Mexico and Florida Straits. In *Issledovaniya Tsentral 'no Amerikanskikh morey (Studies on the Central American Seas), No. 1*, 81-90. Kiev: Noukova Dumka Publishing House.
Jannke, T. E. 1971. *Abundance of young sciaenid fishes in Everglades National Park, Florida, in relation to season and other variables.* Florida Sea Grant Tech. Bull. No. 11.
Johansson, J. O. R. 1984. Plankton. In *The ecology of the South Florida coral reefs: A community profile*, ed. W. C. Jaap, 49-51. U.S. Fish and Wildlife Service, Division of Biological Services, Washington, DC. FWS/OBS-82/08.
Jones, J. A. 1963. Ecological studies of the southeastern Florida patch reefs. Part 1. Diurnal and seasonal changes in the environment. *Bull. Mar. Sci. Gulf Caribb.* 13:282-307.
Kasahara, S., S. Uye, and T. Onbe. 1974. Calanoid copepod eggs in sea-bottom muds. *Mar. Biol.* 26:167-171.
Kelly, J. A., Jr., and A. Dragovich. 1967. Occurrence of macrozooplankton in Tampa Bay, Florida and the adjacent Gulf of Mexico. *Fish. Bull.* 66:209-221.
Kelley, S., T. Potthoff, W. J. Richards, L. Ejsymont, and J. V. Gartner. 1985. *SEAMAP 1983 - Ichthyoplankton. Larval distribution and abundance of Engraulidae, Carangidae, Clupeidae, Lutjanidae, Serranidae, Sciaenidae, Coryphaenidae, Istiophoridae, Xiphiidae and Scombridae in the Gulf of Mexico.* NOAA Tech. Memo. No. NMFS-SEFC-167.

Khromov, N. S. 1965. Distribution of plankton in the Gulf of Mexico and some aspects of its seasonal dynamics. In *Soviet-Cuban fishery research*, ed. A. S. Bogdanov, 36-56. (IPST Translation) U. S. Document TT69-59016.
King, J. E. 1949. A preliminary report on the plankton of the west coast of Florida. *Q. J. Fla. Acad. Sci.* 12:109-137.
Kondratyeva, T. M., and E. Sosa. 1966. Primary productivity of Cuban coastal waters. In *Issledovaniya Tsentral 'no Amerikanskikh morey (Studies on the Central American Seas), No. 1*, 68-80. Kiev: Noukova Dumka Publishing House.
Lancraft, T. M., T. L. Hopkins, and J. J. Torres. 1988. Aspects of the ecology of the mesopelagic fish *Gonostoma elongatum* (Gonostomatidae, Stomiiformes) in the eastern Gulf of Mexico. *Mar. Ecol. Prog. Ser.* 49:27-40.
Leak, J. C. 1981. Distribution and abundance of carangid fish larvae in the eastern Gulf of Mexico, 1971-1974. *Biol. Oceanogr.* 1(1):1-28.
Lee, T. N., and L. P. Atkinson. 1983. Low-frequency current and temperature variability from Gulf Stream frontal eddies and atmospheric forcing along the southeast U. S. outer continental shelf. *J. Geophys. Res.* 88:4541-4568.
Lee, T. N., I. Brooks, and W. Duing. 1977. *The Florida Current - its structure and variability*. Miami: Univ. Miami Tech. Rep. No. RSMAS 77003.
Lee, T. N., L. P. Atkinson, and R. Legeckis. 1981. Observations of a Gulf Stream frontal eddy on the Georgia continental shelf, April, 1977. *Deep-Sea Res.* 28A:347-378.
Legendre, L., S. Demers, and D. Lefaivre. 1986. Biological production at marine ergocline. In *Ecohydrodynamics*, ed. J. C. Nihoul, 1-29. New York: Elsevier.
Leipper, D. F. 1970. A sequence of current patterns in the Gulf of Mexico. *J. Geophys. Res.* 75:637-657.
Lewis, M. R., J. J. Cullen, and T. Platt. 1983. Phytoplankton and thermal structure in the upper ocean: Consequences of non-uniformity in chlorophyll profile. *J. Geophys. Res.* 88:2563-2570.
Lindall, W. N., J. R. Hall, W. A. Fable, and L. A. Collins. 1973. *A survey of fishes and commercial invertebrates of the nearshore and estuarine zone between Cape Romano and Cape Sable, Florida*. St. Petersburg: National Marine Fisheries Service. NTIS No. PB-235 215.
Loeb, V. J. 1980. Vertical distribution and development of larval fishes in the North Pacific central gyre during summer. *Fish. Bull.* 77:777-793.
Longhurst, A. R. 1967. Diversity and trophic structure of zooplankton communities in the California Current. *Deep-Sea Res.* 14:393-408.
Malone, T. C. 1971. The relative importance of nanoplankton and net-plankton as primary producers in tropical oceanic and neritic phytoplankton communities. *Limnol. Oceanogr.* 16:633-639.
Malone, T. C. 1980. Algal size. In *The physiological ecology of phytoplankton*, ed. I. Morris, 433-463. Berkeley: Univ. of California Press.
Marcus, N. H., and C. M. Fuller. 1989. Distribution and abundance of eggs of *Labidocera aestiva* (Copepoda: Calanoida) in the bottom sediments of Buzzards Bay, Massachusetts, USA. *Mar. Biol.* 100:319-326.
Maul, G. 1977. The annual cycle of the Gulf Loop Current, Part I: Observations during a one-year time series. *J. Mar. Res.* 35:29-47.
McGowan, M. F., and W. J. Richards. 1986. Distribution and abundance of bluefin tuna (*Thunnus thynnus*) larvae in the Gulf of Mexico in 1982 and 1983 with estimates of biomass and population size of spawning stock for 1977, 1978 and 1981-1983. *Int. Commer. Cons. Atl. Tunas, Collective Vol. Sci. Pap.* 24:182-195.
Michel, H. B. 1984. *Chaetognatha of the Caribbean Sea and adjacent areas*. NOAA Tech. Rep. NMFS Circ. 15.
Michel, H. B., M. Foyo, and D. A. Haagensen. 1976. *Caribbean zooplankton*. Washington, DC: Office of Naval Research, Department of the Navy. U.S. Government Printing Office.
Miller, R. J., and R. B. Williams. 1972. Energy requirements and food supplies of ctenophores and jellyfish in the Patuxent River estuary. *Chesapeake Sci.* 13:328-331.
Miller, S. M., H. B. Moore, and H. R. Kvammen. 1953. Plankton in the Florida Current. 1. General conditions. *Bull. Mar. Sci.* 2:465-485.
Miller, W. I., R. T. Montgomery, and A. W. Collier. 1978. A taxonomic survey of the diatoms associated with Florida Keys coral reefs. In *Third International Coral Reef Symposium*, ed. D. L. Taylor, 349-355.
Milliken, D. M., and E. D. Houde. 1984. A new species of Bregmacerotidae (Pisces), *Bregmaceros cantori*, from the western Atlantic Ocean. *Bull. Mar. Sci.* 35(1):11-19.
Mitchum, G. T., and W. Sturges. 1982. Wind driven currents on the West Florida shelf. *J. Phys. Oceanogr.* 12:1310-1317.
Montgomery, R. T., W. I. Miller, and A. W. Collier. 1978. A preliminary investigation of the structure of diatom communities associated with reef habitats of the Florida Keys. In *Third International Coral Reef Symposium*, ed. D. L. Taylor, 357-363.
Morris, I., C. M. Yentsch, and C. S. Yentsch. 1971. The physiological state with respect to nitrogen of phytoplankton from low-nutrient subtropical water as measured by the effect of ammonium ion on dark carbon dioxide fixation. *Limnol. Oceanogr.* 16:859-868.
Murphy, E. B., K. Steidinger, B. S. Roberts, J. Williams, and J. W. Jolley, Jr. 1975. An explanation for the Florida east coast *Gymnodinium breve* red tide of November, 1972. *Limnol. Oceanogr.* 29:481-486.
Niiler, P. P., and W. S. Richardson. 1973. Seasonal variability of the Florida Current. *J. Mar. Res.* 31:144-167.
Ortner, P. B., R. L. Ferguson, S. R. Piotrowicz, L. Chesal, G. Berberian, and A. V. Palumbo. 1984. Biological consequences of hydrographic and atmospheric advection within the Gulf Loop Intrusion. *Deep-Sea Res.* 31:1101-1120.
Owre, H. B., and M. Foyo. 1967. *Copepods of the Florida Current*. Fauna Caribbea, No. 1. Inst. Mar. Sci., Univ. of Miami.
Paluszkiewicz, T., L. P. Atkinson, E. S. Posmentier, and C. R. McClain. 1983. Observations of a Loop Current frontal eddy intrusion onto the West Florida shelf. *J. Geophys. Res.* 88:9639-9652.
Peebles, E. B. 1987. Early life history of the sand seatrout, *Cynoscion arenarius*, in Southwest Florida. M.S. thesis, Univ. of South Florida.
Pierce, E. L. 1951. The chaetognatha of the west coast of Florida. *Biol. Bull. Mar. Biol. Lab. Woods Hole* 100:206-228.
Pierce, E. L. 1954. Notes on the chaetognatha of the Gulf of Mexico. *Fish. Bull., U.S.* 55:327-329.

Porter, K. G., J. W. Porter, and S. L. Ohlhurst. 1978. Resident reef plankton. In *Coral reefs: Research methods*, ed. D. R. Stoddart and R. E. Johannes, 499-515. UNESCO Monogr. Oceanogr. Methodol. No. 4.

Powell, A. B., D. E. Hoss, W. F. Hettler, D. S. Peters, L. Simoneaux, and S. Wagner. 1987. *Abundance and distribution of ichthyoplankton in Florida Bay and adjacent waters*. South Florida Research Center Rep. No. SFRC-87/01.

Powell, A. B., D. E. Hoss, W. F. Hettler, D. S. Peters, and S. Wagner. 1989. Abundance and distribution of ichthyoplankton in Florida Bay and adjacent waters. *Bull. Mar. Sci.* 44(1):35-48.

Reeve, M. R. 1964. Studies on the seasonal variation of the zooplankton in a marine sub-tropical in-shore environment. *Bull. Mar. Sci.* 14:103-122.

Reeve, M. R. 1970. Seasonal changes in the zooplankton of south Biscayne Bay and some problems of assessing the effects on the zooplankton of natural and artificial thermal and other fluctuations. *Bull. Mar. Sci.* 20:894-921.

Reeve, M. R., and L. D. Baker. 1975. Production of two planktonic carnivores (chaetognath and ctenophore) in South Florida inshore waters. *Fish. Bull.* 73:238-248.

Reeve, M. R., M. A. Walter, and T. Ikeda. 1978. Laboratory studies of ingestion and food utilization in lobate and tentaculate ctenophores. *Limnol. Oceanogr.* 23:740-751.

Rehrer, R., A. C. Jones, and M. A. Roessler. 1967. Bottom water drift on the Tortugas Grounds. *Bull. Mar. Sci.* 17:562-575.

Reyes-Vasquez, G. 1970. Studies on the diatom flora living on *Thalassia testudinum* Konig in Biscayne Bay, Florida. *Bull. Mar. Sci.* 20:105-134.

Richards, W. J. 1984. *Kinds and abundances of fish larvae in the Caribbean Sea and adjacent areas*. NOAA Tech. Rep. NMFS (Spec. Sci. Rep. Fish. Ser.) 776.

Richards, W. J., T. Potthoff, S. Kelley, M. F. McGowan, L. Ejsymont, J. H. Power, and R. M. Olvera. 1984. *SEAMAP 1982 - Ichthyoplankton. Larval distribution and abundance of Engraulidae, Carangidae, Clupeidae, Lutjanidae, Serranidae, Sciaenidae, Coryphaenidae, Istiophoridae, Xiphiidae and Scombridae in the Gulf of Mexico*. NOAA Tech. Memo. No. NMFS-SEFC-144.

Riley, G. A. 1938. Plankton studies. 1. A preliminary investigation of the plankton of the Tortugas region. *J. Mar. Res.* 1:335-352.

Roberts, B. S. 1979. Occurrence of *Gymnodinium breve* red tides among the west and east coasts of Florida during 1976 and 1977. In *Proceedings, 2nd International Conference on Toxic Dinoflagellate Blooms*, ed. D. L. Taylor and H. H. Seliger, 199-202. New York: Elsevier.

Rutherford, E. S., T. W. Schmidt, and J. T. Tilmant. 1989. Early life history of spotted seatrout (*Cynoscion nebulosus*) and gray snapper (*Lutjanus griseus*) in Florida Bay, Everglades National Park, Florida. *Bull. Mar. Sci.* 44(1):49-64.

Saksena, V. P., and W. J. Richards. 1986. A new species of gadiform fish, *Bregmaceros houdei*, from the western North Atlantic. *Bull. Mar. Sci.* 38(2):285-292.

Saunders, R. P., and D. A. Glenn. 1969. Diatoms. *Memoirs of the Hourglass Cruises, Vol. I, Pt. III.*

Saunders, R. P., B. I. Birnhak, J. T. Davis, and C. L. Wahlquist. 1967. Seasonal distribution of diatoms in Florida inshore waters from Tampa Bay to Caxambas Pass, 1963-1964. In *Red tide studies, Pinellas to Collier counties, 1963-1966, A symposium*, 48-78. Fla. Bd. Conserv. Mar. Lab. Prof. Pap. Ser. No. 9.

Schomer, N. S., and R. D. Drew. 1982. *An ecological characterization of the lower Everglades, Florida Bay and the Florida Keys*. FWS/OBS-82/58.1. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Smith, D. G. 1980. Early larvae of the tarpon, *Megalops atlantica* Valenciennes (Pisces: Elopidae), with notes on spawning in the Gulf of Mexico and the Yucatan Channel. *Bull. Mar. Sci.* 30(1):136-141.

Smith, P. E. 1971. *Distributional atlas of zooplankton volume in the California Current region, 1951 through 1966*. CalCOFI Atlas, No. 13.

Squires, A. P. 1984. The distribution and ecology of zooplankton in Charlotte Harbor, Florida. M.S. thesis, Univ. of South Florida.

Steele, J. H. 1964. A study of production in the Gulf of Mexico. *J. Mar. Res.* 22:211-222.

Steidinger, K. A. 1972. Dinoflagellate distribution. In *Chemistry, primary productivity, and benthic algae of the Gulf of Mexico, folio 22*, ed. V. C. Bushnell, 23-25. New York: American Geographical Society.

Steidinger, K. A. 1973. Phytoplankton ecology: A conceptual review based on eastern Gulf of Mexico research. *CRC Crit. Rev. Microbiol.* 3:49-68.

Steidinger, K. A., and J. Williams. 1970. Dinoflagellates. *Memoirs of the Hourglass Cruises, Vol. II.*

Steidinger, K. A., J. T. Davis, and J. Williams. 1967. Dinoflagellate studies on the inshore waters of the west coast of Florida. In *Red tide studies, Pinellas to Collier counties, 1963-1966, a symposium*, 4-47. Prof. Pap. Fla. Bd. Conserv. Mar. Lab., No. 9.

Stepien, J. C. 1980. The occurrence of chaetognaths, pteropods and euphausiids in relation to deep flow reversals in the Straits of Florida. *Deep-Sea Res.* 27A:987-1011.

Sullivan, J. R. 1979. *The stone crab, Menippe mercenaria, in the Southwest Florida fishery*. Fla. Mar. Res. Publ. No. 36.

Tabb, D. C, D. L. Dubrow, and A. E. Jones. 1962. *Studies on the biology of the pink shrimp, Penaeus duorarum Burkenroad, in Everglades National Park, Florida*. Fla. State Bd. Conserv. Tech. Ser. No. 37.

Tester, P. A., P. K. Fowler, and J. T. Turner. 1989. Gulf Stream transport of the toxic red tide dinoflagellate, *Ptychodiscus brevis* from Florida to North Carolina. In *Proceedings, Symposium on novel phytoplankton blooms: Causes and impacts of recurrent brown tides and other unusual blooms*, ed. E. M. Cosper, E. J. Carpenter, and V. M. Bricelj. Berlin: Springer-Verlag.

Turner, J. T., and T. L. Hopkins. 1985. The zooplankton of Tampa Bay: A review. In *Proceedings, Tampa Bay area scientific information symposium*, ed. S. F. Treat, J. L. Simon, R. R. Lewis III, and R. L. Whitman, Jr., 328-344. Florida Sea Grant College Rep. No. 65.

Turner, J. T., S. B. Collard, J. C. Wright, D. V. Mitchell, and P. Steele. 1979. Summer distribution of pontellid copepods in the neuston of the eastern Gulf of Mexico continental shelf. *Bull. Mar. Sci.* 29:287-297.

Vandevelde, T., L. Legendre, J.-C. Therriault, S. Demers and A. Bah. 1987. Subsurface chlorophyll maximum and hydrodynamics of the water column. *J. Mar. Res.* 45:377-396.

Vargo, G. A. 1968. Studies of phytoplankton ecology in tropical and subtropical environments of the Atlantic Ocean. Part 2. Quantitative studies of phytoplankton distribution in the Straits of Florida and its relation to physical factors. *Bull. Mar. Sci.* 18:5-60.

Vargo, G. A., K. L. Carder, W. Gregg, E. Shanley, C. Heil, K. A. Steidinger, and K. Haddad. 1987. The potential contribution of primary production by red tides to the West Florida shelf ecosystem. *Limnol. Oceanogr.* 32:762-767.

Vukovich, F. M., B. W. Crissman, M. Bushnell, and W. J. King. 1979. Some aspects of the oceanography of the Gulf of Mexico using satellite and *in situ* data. *J. Geophys. Res.* 84:7749-7768.

Walsh, J. J. 1969. Vertical distribution of antarctic phytoplankton standing crops in the southern ocean with that of the Florida Strait. *Limnol. Oceanogr.* 14:86-94.

Walsh, J. J. 1983. Death in the sea: Enigmatic phytoplankton losses. *Prog. Oceanogr.* 12:1-86.

Williams, J., W. F. Grey, W. B. Murphy, and J. J. Crane. 1977. Drift bottle analyses of eastern Gulf of Mexico surface circulation. *Memoirs of the Hourglass Cruises, Vol. IV, Pt. III.*

Woodmansee, R. A. 1958. The seasonal distribution of the zooplankton off Chicken Key in Biscayne Bay, Florida. *Ecology* 39:247-262.

Woodward-Clyde Consultants and Skidaway Institute of Oceanography. 1983. *Southwest Florida shelf ecosystems study. Year 2 modification, final report.* New Orleans: U.S. Department of the Interior, Minerals Management Service.

Yashnov, V. A. 1962. Vertical distribution of the mass of zooplankton in the tropical region of the Atlantic Ocean. *Oceanology* 136-141:4-6 (English Translation).

Yentsch, C. M., C. S. Yentsch, and J. P. Perras. 1972. Alkaline phosphatase activity in the tropical marine blue-green alga, *Oscillatoria erythraea* ("*Trichodesmium*"). *Limnol. Oceanogr.* 17:772-774.

Yoder, J. A. 1985. Environmental control of phytoplankton production on the southeastern U.S. continental shelf. In *Oceanography of the southeastern U.S. continental shelf*, ed. L. P. Atkinson, D. W. Menzel, and K. A. Busch, 93-103. Washington, DC: American Geophysical Union.

Yoder, J. A., and A. Mahood. 1983. Primary production in Loop Current upwelling. In *Southwest Florida shelf ecosystems study. Year 2 modification*, 219-278. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Yoder, J. A., S. S. Bishop, L. P. Atkinson, C. R. McClain, T. Paluszkiewicz, and A. Mahood. 1983. *Effects of the Loop Current on phytoplankton production of the Southwest Florida continental shelf.* Unpubl. manuscript.

CHAPTER 7
FISH COMMUNITIES AND FISHERIES BIOLOGY

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INTRODUCTION

South Florida's marine habitats support a diverse fish and shellfish fauna that includes numerous species of recreational and/or commercial importance. There are several reasons why these fishery resources are of concern with respect to oil and gas operations. First, many fishery species are dependent, at one life stage or another, upon the complex, interrelated system of mangrove forests, coral reefs, and seagrass beds described in **Chapter 4**. Therefore, oil and gas operations or other human activities that might result in damage to these coastal and nearshore systems could affect area fish populations and fishery resources. Second, most species of commercially and recreationally valuable fish have pelagic eggs that undergo initial development in surface waters (see the Ichthyoplankton section in **Chapter 6**), where they are vulnerable to oil spills. Finally, because several fishery species in South Florida are overexploited, any additional source of mortality from human activities is of concern.

This chapter is divided into two parts. The first part discusses South Florida fish communities, in the context of the region's marine habitats. The second part discusses the biology of commercially and recreationally important fishery species. Fishery statistics are not included in this chapter; those data are presented in **Chapter 11**.

FISH COMMUNITIES

William S. Alevizon

Introduction

The intent of this section is to summarize available information on fish assemblages associated with marine and estuarine habitats of South Florida. In terms of fish life, these are rich waters inhabited by a highly diverse array of species (Longley and Hildebrand 1941; Starck 1968). There are several good reasons for this. The first is the unusual geography of the Florida Keys, which occur as a chain of islands adjoining a continent. Tropical fish faunas may be classified as being primarily continental (characterized by turbid waters, mud or silt substrates, and lack of coral reefs), or insular (characterized by clear water, calcium carbonate substrates, and frequent coral reefs) (Robins 1971). Some fish families (e.g., Sciaenidae, Sparidae, etc.) are primarily (but *not* exclusively) continental, while others (e.g., Chaetodontidae, Holocentridae, Scaridae, etc.) are primarily insular. As Gilbert (1972, p. 137) points out, "Varying degrees of mixing of the insular and continental faunas occur in Florida ... The richness of the Florida Keys fish fauna is due in large degree to this mixing effect."

The waters of South Florida encompass several distinct aquatic environments, each of which is inhabited by a different fish fauna. The waters seaward (south) of the Florida Keys from the shoreline through the Straits of Florida are occupied by a wholly tropical and primarily insular fauna similar to that of the Bahamas and other insular regions of the Caribbean. To the north of the Keys lie the waters of the eastern Gulf of Mexico and Florida Bay. The fish fauna here is primarily a warm temperate continental fauna typical of the west coast of Florida. The marine waters of the western portion of this region (Gulf of Mexico) grade into the estuarine waters of Florida Bay to the east, and the fish fauna is accordingly modified.

Because the Florida Keys are a chain of islands rather than a continuous land mass, there are varying degrees of mixing of these dissimilar faunas along the length of the Keys. The extent of this mixing depends to a large extent on the degree of isolation provided by the land masses of the islands themselves. Nonetheless, the faunas are reasonably distinct over most of the area encompassed by these two regions as defined herein, and thus are so treated in this section. The abundance and diversity of fishes in these waters also reflects, to some degree, the diversity and availability of productive habitats. Frequently, mangroves, lush seagrass meadows, desert-like sand flats, benthic sargassum forests, and a variety of coral reef habitats all occur within the relatively short distance of 15 to 18 km (8 to 10 nmi) from shore.

The fish assemblages occupying major habitat types of these waters have been subject to varying degrees of scientific scrutiny; most have been subject to little more than cursory examination. Because the purpose of this review is to summarize what is known rather than to speculate on what is not, the length of the various subsections reflects the amount of available material, rather than the relative ecological or economic value of the fishes of each habitat. I have organized the review by discussing separately the fish assemblages inhabiting each of the aquatic environments defined above (i.e., waters seaward of the Keys, which will be referred to as the Straits of Florida area, and the waters north of the Keys, which includes Florida Bay and the Southwest Florida shelf). There are many ways in which the habitats occurring in waters of South Florida might be classified or distinguished. I have attempted to use what seemed the most simple and logical scheme to me; others might disagree, but this fact merely serves to emphasize the point that boundaries between habitats are necessarily arbitrary; seldom do clearly defined demarcations exist, either between habitats or the fish assemblages associated with them. As Weinstein and Heck (1979) noted, "In general, many fishes do

not seem to recognize the seagrass meadows, coral reefs, and intervening sandy areas as distinct habitats, but apparently perceive them as a spatial continuum." Transitional areas where biotopes and/or habitats grade into one another may be among the most interesting and diverse portions of the environment, yet these have been particularly neglected in the literature, primarily because they are difficult to define or delimit for study.

Descriptions of fish communities frequently classify fishes by habits and home range. Some species may be considered true residents, in the sense that they conduct all or most of their usual activities within the boundaries of that habitat. Others are considered visitors; these are fishes that are regularly present in a given habitat, but also regularly include other habitats in their activity patterns. Still others are termed transients: fishes that occasionally pass through the habitat en route to other areas, but interact minimally if at all with other residents or visitors. Such distinctions are useful, particularly in the context of predicting the vulnerability of species and/or communities to various environmental traumas. Destruction or damage to a habitat would generally be expected to have a greater effect on obligate residents of that habitat than on visitors. Other types of ecological information particularly useful are feeding habits, reproductive habits, and movement patterns. Unfortunately, only for a relative few of the hundreds of fish species residing in waters of South Florida is sufficient information available to predict probable responses to ecological perturbations.

While our understanding of the autecology of the component species is fragmentary and far from complete, our understanding of species interactions within any given habitat is even more limited. At a higher level, the interactions between species assemblages of different habitats, although unquestionably critical to our overall understanding of these complex systems, is almost totally unexplored. Perhaps one of the most useful aspects of synthesis documents such as this is to provide a perspective on the current degree of knowledge about a particular area, and thus provide direction for research into neglected areas.

Straits of Florida Area

The Straits of Florida area consists of two regions: inshore waters, extending from the seaward (southern) shoreline of the Florida Keys out to the edge of the continental shelf, and the offshore waters of the Straits proper. Major inshore habitats include reefs, seagrass beds, sand flats, and mangroves. Major offshore habitats include pelagic zones (epipelagic, mesopelagic, bathypelagic) as well as the deep benthic.

Inshore Habitats

The inshore waters of this region can be regarded as a single, complex, integrated aquatic environment, composed of a number of distinctive (but interactive) habitats. Dividing such systems into discrete "communities" based on recognizable habitat boundaries may be convenient from an organizational standpoint, or from the perspective of a single research project. However, it is evident that many, if not most, of the fishes of the region use a number of different habitats, either on a daily basis and/or at different stages of the life cycle. As an example of the former (daily) use patterns of different habitats, many of the Haemulidae (grunts) as well as Lutjanidae (snappers) remain sheltered on coral reefs by day, but forage far out into seagrass beds at night (Starck and Davis 1966; McFarland et al. 1979). A good example of the use of different habitats at different stages of the life cycle is that of the great barracuda *Sphyraena barracuda*. Bohlke and Chaplin (1968, p. 198) report that, "specimens up to a foot in length prefer sandy and weedy shallows and seldom are found offshore or on the reefs, these areas being the preserves of individuals two feet long and larger." Such patterns

are common among the larger fishes of the region (Weinstein and Heck 1979). However, many of the smaller species (e.g., damselfishes) are more limited in their use of space resources. In some cases, most of their life cycle is spent within a few square meters.

Thus, the environmental conditions in any habitat type will undoubtedly have direct and indirect effects on the fishes inhabiting others. The approach of Starck (1968), who treated the fishes from the shoreline out to the deep reefs as a single "community," is the most realistic view. However, because most scientific studies of fish assemblages have been confined to one type of habitat, and because each habitat has a distinct and characteristic fish assemblage, it is convenient to discuss them in that manner.

Coral Reefs. As habitat for fishes, coral reefs are characterized by extreme topographic complexity combined with high primary productivity, thereby providing unusually rich sources of both food and shelter for resident fishes. It has been generally assumed that it is primarily the latter (shelter) which accounts for the unparalleled abundance and diversity of fish life observed around coral reefs. Coral reefs of the tropical western Atlantic are frequently found in close association with extensive seagrass beds and mangrove-lined shores. Thus, in these areas of high primary production, the reefs often represent the only habitat with sufficient structural complexity to provide shelter for larger fishes. It is not surprising then that reefs serve as focal points for aggregations of a wide variety of fish life. In the Indo-Pacific region, particular reef areas may be frequented by over 2,000 fishes species, and in the Caribbean by over 500 (Starck 1968). Of these, many are not obligate residents, but also occur regularly in non-reef areas. However, the presence of reefs unquestionably increases the overall abundance of many species considered merely visitors or transients on coral reefs.

On reefs, fishes are diverse in size, from diminutive cardinal fish which mature at an inch or so in length, to sharks and groupers that are meters in length and weigh hundreds of kilograms. Similarly, the diversity of form is remarkable, ranging from the swift, sleek barracuda to the bizarre symmetry of the clumsy boxfish. Apparently it is the diversity of living spaces and food resources available on the reef that makes this diversity of form and size possible in such relatively restricted areas.

The forces and/or processes that shape and maintain the structure of coral reef fish communities have been the subject of active debate during the last decade. Traditionally, coral reef fish communities have been described as deterministic; that is, they were seen as essentially stable equilibrium communities maintained by complex ecological and behavioral interrelationships (Smith 1973; Hobson 1974; Smith and Tyler 1975; Hobson and Chess 1976, 1978; Molles 1978; Anderson et al. 1981; Greenfield and Greenfield 1982; Alevizon et al. 1985). Community structure was believed to be largely determined by reef structure, prevalent currents, nature of nearby habitats, etc. More recently, this view has been challenged by a stochastic approach, in which reef fish communities were seen as unstable assemblages that unpredictably varied in space and time as the result of a number of essentially random processes, including chance recruitment of larvae (Russel et al. 1974; Sale and Dybdahl 1975; Sale 1977; Williams and Sale 1981; Sale and Douglas 1984).

To a large extent, this controversy has subsided, as most (but not all) current workers tend to agree that either view may be correct, depending on size of the study area (Brock et al. 1979; Anderson et al. 1981; Ogden and Ebersole 1981; Sale and Douglas 1984). For small-scale areas, occupied by relatively few species (e.g., single coral heads), the stochastic view appears reasonably applicable. For large reef areas (e.g., hundreds of meters), occupied by many species, community structure is reasonably predictable on the basis of reef structure and other environmental factors.

Coral reefs of the tropical western Atlantic region have a characteristic zonation pattern much simpler than that found among Indo-Pacific reefs. This pattern has been described by reef investigators (Goreau 1959; Milliman 1973) and has been shown to clearly affect reef fish distribution and abundance patterns of the region (Alevizon et al. 1985). This basic pattern, although highly variable from site to site, appears to be recurrent throughout the Caribbean basin, including the Florida Keys. Although limited in extent and highly patchy in distribution, reasonably well-developed representatives of major zones are present in the Florida Keys.

The living coral reefs in the Florida Keys represent the scattered fragments of what was once a much more extensive living reef system. In addition to the deep and shallow reefs, there are substantial areas composed of the dead and largely eroded limestone bases of this earlier system. These are called hardgrounds. Thus, the term "coral reef" as used herein in the context of the Florida Keys includes several distinct habitat types (see **Chapter 4**). The living reef areas are topographically much more complex and contain a greater variety of food and shelter resources than do hardground areas. The two types of reef habitat are treated separately in this section.

Living reefs: The reef fish communities of the Florida Keys appear generally similar in structure to those of the remainder of the Caribbean region, with differences primarily in relative abundances of species rather than species composition (Starck 1968). Although Florida reefs undoubtedly experience periodically lower temperatures than reef areas of the Caribbean, there is no evidence to suggest that this factor (temperature) has resulted in specific differences in resident fish communities. Starck (1968) concluded that the relatively minor differences between Floridian and Bahamian reef fish assemblages are probably attributable to the heavier sediment load present in the Florida Keys. Nonetheless, the fish communities associated with living reef areas of the South Florida region appear to vary considerably both spatially (Bannerot and Schmale 1982) and temporally (Alevizon and Greene in prep.). Therefore, generalizations should be made with caution concerning the particular structure of these diverse and complex communities.

The living reefs of the South Florida region may be subdivided into those occurring in shallow water ($\leq$ about 30 m), and those occurring in deeper water. The 30 m division is arbitrary, but convenient from the standpoint that this depth roughly represents the practical limit for direct observation of fishes using conventional scuba. Beyond this depth, visual censusing from submersibles or remotely operated vehicles are the only practical methods of assessing reef fish assemblages. For this reason, much less is known about the deep reef communities. Shallow and deep reef fish assemblages are discussed separately here, but these represent the two extremes of one continually grading system.

The first extensive ichthyological survey of the Florida reef fishes, much of which incorporated direct observation by hard-hat diving, was by Longley and Hildebrand (1941). They reported about 300 species that might be properly considered reef inhabitants. Starck (1968) conducted what remains today the most comprehensive survey of the ichthyofauna of the Florida Keys, using scuba and ichthyocides (fish poisons). He recorded some 517 species, 389 of which he considered reef residents, from waters off Islamorada in the Upper Keys.

Recent quantitative studies of shallow (<30 m) reef fish assemblages of the South Florida region have been concentrated in two main areas: the Key Largo and Looe Key National Marine Sanctuaries. The continuing data accumulating from these sites, and their protected status, make these areas unique and invaluable resources in terms of future ecological assessment of fish assemblages of the region. Included in these works are the studies of Alevizon and Brooks (1975) who used cinetransects to compare Key Largo fish assemblages with those of a Venezuelan reef. These same filmed samples

were also compared with similar samples obtained at the same sites in 1984 to evaluate changes in the Key Largo fish communities over a 10-year period (Alevizon and Greene in prep.). Jones and Thompson (1978) developed a rapid visual technique to assess fish assemblages of some Key Largo reefs as well as reef areas of the Tortugas. Bannerot and Schmale (1982) used the same technique to assess a variety of fish communities of the Key Largo National Marine Sanctuary. Bohnsack and Bannerot (1986) developed a stationary visual census technique to assess reef fish populations at Looe Key, and Bohnsack et al. (1987) conducted an extensive survey of fish assemblages of the Looe Key National Marine Sanctuary. Following the grounding of the freighter *Wellwood* in 1984, the National Marine Sanctuary Division of NOAA initiated a comprehensive and continuing study of the fish assemblages on and around Molasses Reef (Key Largo).

Because these studies have used substantially different censusing techniques, comparative analysis of their respective results is tenuous at best. Results obtained by different methods have been shown to be highly dependent on the methodology employed, in terms of quantification of community structure (Greene and Alevizon 1989). Even when various methods were used at the same limited reef site and at essentially the same time, major discrepancies were apparent in terms of quantifying relative abundance of species (Alevizon in prep.). However, it appears that these methods are comparable for simply ranking species in terms of abundance.

None of the methods used to quantify the structure of reef fish communities of Florida reefs have demonstrated an acceptable level of precision or accuracy to suggest that they may be considered reliable estimators of actual or relative abundances of component species. This point is particularly relevant for possible future investigations purporting to investigate temporal changes in these fish assemblages, or to assess the impact of particular catastrophic events. Nonetheless, much baseline information exists on reef fish community structure from a variety of reef habitats in the Florida Keys. This information will undoubtedly become even more valuable in the future, and will be helpful in assessing long-term trends as well as traumatic episodes, provided it is used with the aforementioned limitations in mind.

There have been several ecological studies of particular species or groups of species of reef fishes of the Florida Keys, although much of this work exists only in the form of unpublished theses and dissertations (e.g., Davis 1967; Emery 1968; Alevizon and Landmeier 1984). It is beyond the scope of this document to summarize all this material. In some cases, these studies may eventually prove more useful in assessing certain types of ecological changes than the more general community studies described above. The main reason is that those more limited studies usually incorporate more accurate quantification of ecological parameters.

As is typical of shallow Caribbean reef systems in general, the non-cryptic resident shallow reef fish fauna of South Florida is dominated in terms of both numbers of species and numbers of individuals by seven families: Acanthuridae (surgeonfishes), Chaetodontidae (butterflyfishes), Haemulidae (grunts), Labridae (wrasses), Lutjanidae (snappers), Pomacentridae (damselfishes), and Scaridae (parrotfishes) (**Table 7.1**). These families consistently include the vast majority of species (i.e., Bannerot and Schmale 1982; Bohnsack and Bannerot 1986; Alevizon and Greene in prep.). However, probably because of localized variability in such ecological factors as reef structure, currents, sedimentation, larval recruitment, etc., the specific structure of fish communities, in terms of relative abundances of particular species within these groups, often varies substantially from reef to reef. The cryptic fauna notably includes numerous members of the families Apogonidae (cardinalfishes), Blenniidae (combtooth blennies), Gobiidae (gobies), and Holocentridae (squirrelfishes). Quantitative studies of these fishes have lagged behind those of the non-cryptic fauna.

Table 7.1. Dominant fish families associated with marine habitats in the study area.

Habitat	Dominant Families		Reference(s)
	Scientific Name	Common Name	
STRAITS OF FLORIDA			
Shallow Coral Reefs (<30 m)	Acanthuridae	surgeonfishes	Bannerot and Schmale (1982)
	Chaetodontidae	butterflyfishes	Bohnsack and Bannerot (1986)
	Gobiidae	gobies	Greene and Alevizon (1989)
	Haemulidae	grunts	
	Labridae	wrasses	
	Lutjanidae	snappers	
	Pomacentridae	damselfishes	
	Scaridae	parrotfishes	
Deep Coral Reefs (>30 m)	Chaetodontidae	butterflyfishes	Colin (1974, 1976)*
	Gobiidae	gobies	
	Grammidae	basslets	
	Holocentridae	squirrelfishes	
	Labridae	wrasses	
	Serranidae	sea basses	
Seagrass Beds	Apogonidae	cardinalfishes	Springer and McErlean (1962)
	Balistidae	leatherjackets	Alevizon and Gorham (1989)
	Clinidae	clinids	Robblee and Zieman (1984)*
	Gobiidae	gobies	
	Haemulidae	grunts	
	Labridae	wrasses	
	Lutjanidae	snappers	
	Scaridae	parrotfishes	
	Serranidae	sea basses	
Sand Flats	Gobiidae	gobies	Alevizon and Gorham (1989)
	Haemulidae	grunts	
	Labridae	wrasses	
	Lutjanidae	snappers	
Epipelagic	Carangidae	jacks	
	Coryphaenidae	dolphins	
	Exocoetidae	flyingfishes	
	Istiophoridae	billfishes	
	Scombridae	mackerels	
FLORIDA BAY (Mangrove, Seagrass)	Engraulidae	anchovies	Carter et al. (1973)
	Gerreidae	mojarras	Thayer et al. (1987)
	Lutjanidae	snappers	
	Mugilidae	mullets	
	Sciaenidae	drums	
	Sparidae	porgies	
SOUTHWEST FLORIDA SHELF (Demersal)	Bothidae	lefteye flounders	Juhl (1966)
	Haemulidae	grunts	Darcy and Gutherz (1984)
	Myliobatidae	eagle rays	
	Sciaenidae	drums	
	Serranidae	sea basses	
	Sparidae	porgies	

* Studies conducted at other Caribbean sites.

Predation is unquestionably the major cause of reef fish mortality (Goldman and Talbot 1976; Sale 1980). Because predators differ in their abilities to utilize different types of prey, it follows that the nature of piscivorous predators in an area may have major effects on the structure of fish assemblages. The major large piscivorous predator of these shallow reef communities of South Florida is the great barracuda *Sphyraena barracuda*. In contrast to Bahamian reef systems, other large piscivores such as serranids (groupers and hinds) and large snappers are relatively rare. Similarly, sharks are seldom seen. Although actual data are lacking, much of this discrepancy appears to be a result of human impact on these systems. The reefs of South Florida have been, and continue to be, intensively fished for grouper and snapper both by hook-and-line as well as spearfishing. Bohnsack (1982) has documented an increase in these fishes in the Looe Key National Marine Sanctuary after that area was closed to spearfishing. Sharks seem to avoid areas of heavy boating and diving. Based on 15 years of diving in Florida and the Caribbean, I believe that sharks are more common in areas seldom frequented by humans. Barracudas may be considered visitors on any particular reef because they typically have sizeable home ranges including many reefs and other habitats. Other notable piscivorous visitors to these reefs include several members of the family Carangidae (jacks) as well as Megalopidae (tarpon). These fishes are frequently observed in shallow reef areas of the region and presumably take their toll of prey.

The ability of shallow coral reef fish communities of this region to recover from man-made or natural disasters is not well understood, although several notable studies investigated this problem. Smith (1973) conducted experiments using the ichthyocide rotenone on small patch reefs in the Bahamas, and concluded that "the effects of sampling (fish removal) disappear four to nine months later." Bohnsack (1983) studied the effects of a record-breaking cold spell on fishes inhabiting a series of artificial reefs in the Florida Keys. He reported that "the rapid return of all community parameters to pre-disturbance levels suggest that reef fish communities are highly resilient." In contrast, effects of the wholesale destruction of a section of reef by the grounding of the freighter *Wellwood* in 1984 led to major (and still lasting), large-scale changes in the fish communities of the damaged area (L. Greene, pers. comm.). Thus, in general, it appears that reef fish communities are resilient to a variety of short-term disturbance, *provided* the reef habitat itself is relatively undamaged. Furthermore, because most small-sized reef fishes are annuals, environmental disturbance during times of spawning may "result in an abrupt and drastic reduction in abundance from one season to the next" (Gilbert 1972).

Deep reefs: As a home for fishes, deep (>30 m) reefs of the tropical western Atlantic share many common characteristics with shallow reefs of this region, including, most notably, a diversity of shelter, species, and food resources. However, there are also some notable differences which unquestionably account for the marked differences in the fish communities associated with each type of habitat. Most notably, because of decreased light penetration, primary production is much lower on the deep reefs. Thus, the abundance of primarily herbivorous fishes is likewise decreased. Surgeonfishes, parrotfishes, and many of the demersal territorial damselfishes, which are prominent in shallow reef systems, become rare or absent below 40 to 50 m (Colin 1974, 1976). Nocturnally foraging grunts (*Haemulon* spp.) and snappers (*Lutjanus* spp.) which feed largely in shallow seagrass beds likewise decline sharply in abundance.

Thus, in contrast with shallow reefs, the deep reef fish communities of the Caribbean are characterized by the predominance of strictly carnivorous, non-schooling species including members of the families Gobiidae (gobies), Grammidae (basslets), Holocentridae (squirrelfishes), Labridae (wrasses), and Serranidae (sea basses) (**Table 7.1**). The only group known to be at least partially herbivorous, commonly observed on deep Caribbean reefs, are the Chaetodontidae (butterflyfishes); however,

even these are probably primarily carnivorous at these depths. Additionally, as might be predicted by the more offshore location of deep reefs, these assemblages are more likely to include a much greater proportion of visitors or transients than shallow reef assemblages (Moffitt et al. 1989). While published information on direct observation of deep reef fishes of the South Florida region is lacking, the general similarities between other components of the Floridian reef ichthyofauna with that of the insular Caribbean suggest that there should be strong similarities.

Hardgrounds: The term "hardgrounds" is used here to denote areas of low-relief (generally <2 m) limestone with a low percentage of cover by live scleractinian corals. Such areas represent the eroded bases of earlier reef systems, and may in many areas of South Florida exceed the area occupied by live coral. Hardgrounds frequently support luxurious growths of octocorals of the families Gorgonidae (sea fans) and Plexauridae (sea whips). Sponges are also common in these areas. The limestone substratum is perforated by numerous holes and fissures of varying dimension, creating additional shelter for fishes. In many areas of South Florida, these formations also form a characteristic "spur and groove" system, such that finger-like projections of reef are interspersed with sand channels. The overall vertical relief of these systems is generally no more than about 2.5 m, with about 1 m due to the sand-reef interface and the remaining 1.5 m due largely to octocorals. Although the relief and topographic complexity of this system are rather low compared to "living" coral reefs, it is nonetheless sufficient to support a reasonably diverse and abundant fish assemblage. The distribution of this habitat type through the Florida Keys is discontinuous. Hardgrounds occur frequently in very shallow waters (<4 m) immediately seaward of the shoreline of the Keys. They are absent or infrequent from Hawk Channel to the outer edge of the Reef Tract, where they reappear in depths ranging from about 4 to 20 m.

There is little quantitative information available on the fish assemblages of this particular habitat type. Colton (1978) compared the fish assemblage of an offshore hardground area (Crocker Reef) to that of an inshore "live coral" patch reef (Hens and Chickens Reef), both of which were roughly located off Windley Key. In terms of species composition, he found the two sites to be comparable. Of 111 species observed at either area, 65 were common to both, 31 were found only at Hens and Chickens, and 15 found only at Crocker. However, he found major differences in abundance patterns of the component species. These he attributed mainly to differences in reef structure and nature of adjacent habitats. The primary difference between the two areas includes predominance of small, non-schooling forms on the hardground reef, which apparently "lacks the extensive vertical relief required for the shelter requirements of such [schooling] species" (Colton 1978), and the lower species diversity of the hardground reef area.

Richardson (1986) conducted a limited quantitative study of the fish assemblage of a shallow (nearshore) hardground area off Bahia Honda Key. Larger fishes were censused by timed visual counts. Smaller cryptic forms were censused by a quadrat procedure. The depth range of the samples was 1 to 3 m, and samples were collected only over a 5-week period in mid-winter (December through January). Although this study suffers from limitations, it is discussed here because it represents the only quantitative data for fishes representative of an inshore hardground habitat. Richardson's (1986) results suggest that a single wrasse (*Halichoeres bivittatus*) was the dominant species, comprising nearly 25% of the fishes observed. This finding is similar to that of Colton (1978) who reported the wrasse *Halichoeres garnoti* to be the dominant species at the offshore hardground habitat. Of the remaining fishes, Richardson (1986) noted that, "most ... were <4 cm in length or had juvenile color patterns." This suggests that these shallow-water, inshore, hardground areas may represent a major "nursery" area for many species that occur as adults in more offshore reef (and other) habitats.

Despite the lack of attention given to hardground reefs by fish ecologists, the value of this habitat in terms of fish ecology should not be under-emphasized. Hardgrounds comprise a large extent of the "live bottom" throughout the South Florida region, and thus, in total, represent a habitat supporting a very high biomass of fishes.

A weakness in reef fish investigations of South Florida is that most were done solely during daylight hours. Nonetheless, the relatively few nocturnal studies that have been conducted in South Florida (e.g., Starck and Davis 1966; Colton 1978), as well as in other areas of the Caribbean (e.g., Collette and Talbot 1972; Weinstein and Heck 1979), have made it clear that at night, the fish communities of reef areas differ substantially from those of daylight hours, both in terms of species composition, relative abundance of species, general activity patterns, and individual behavior.

Seagrass Beds. Seagrasses form an extensive and important habitat for inshore marine fishes of the tropical western Atlantic region, including South Florida (**Table 7.1**). As well as supporting an assemblage of primary residents, seagrass beds function both as a major foraging area for reef fishes (Longley and Hildebrand 1941; Randall 1963; Starck and Davis 1966; Ogden and Zieman 1977; Robblee and Zieman 1984) and a nursery area for many species that primarily occupy reefs as adults (Weinstein and Heck 1979; Tabb et al. 1962; Thayer et al. 1987).

Seagrasses have less habitat structure than reefs, with little vertical relief or shelter for longer fishes. Typically, the only large fishes seen by day in seagrass areas are those relatively immune to predation, such as the trunkfishes (Ostraciidae) or larger predators themselves (i.e., barracudas). Thus, it is not surprising that by day, seagrass beds of the Caribbean region support a relatively simple fish assemblage. Quantitative sampling of seagrass areas in the U.S. Virgin Islands revealed that the diurnal fish assemblage was largely dominated by a few small (<12 cm standard length) scarids (parrotfishes), labrids (wrasses), clinids, and syngathids (pipefishes) (Robblee and Zieman 1984). Similar results were obtained in Panama by Weinstein and Heck (1979).

However, with the cover provided by darkness, a diversity of predatory fishes move away from their diurnal, shelter sites (e.g., reefs) to actively forage and feed in the seagrass beds (Davis 1967; Hobson 1973; McFarland et al. 1979; Helfman et al. 1982). These fishes feed on a variety of motile invertebrates, and on each other (Randall 1967). Most notable are certain of the grunts (*Haemulon* spp.), snappers (*Lutjanus* spp.), and cardinalfish (*Apogon* spp.). At the same time, many of the diurnally dominant fishes become inactive at night, seeking shelter at the bases of the seagrass blades or in the underlying sediments (Lobel and Ogden 1981).

The forces and processes that determine the structure of seagrass fish assemblages at any given site are poorly understood, despite the extensive literature on seagrass fish ecology. In general, seagrass habitat is believed to enhance fish abundance and diversity in much the same manner as coral reefs, but at a less dramatic scale; by providing food and shelter (Moyle and Cech 1988). However, factors determining the composition of the fish assemblages appear varied and complex, including such parameters as seagrass biomass and blade density (Stoner 1983), nature of microhabitats within the seagrass bed (Weinstein and Heck 1979), water movement (Adams 1976), and other physical/chemical parameters. Sogard et al. (1987, p. 25) suggested that, "species composition at different sites is proposed to be a result of complex interactions between the deterministic influence of habitat quality and the stochastic influence of larval availability." Pollard (1984) has summarized available literature over broad geographic range in a comprehensive review of seagrass fish community ecology.

Most studies of seagrass fish communities of the South Florida region have been conducted in waters of the Gulf of Mexico/Florida Bay (north) side of the Florida Keys. Surprisingly few quantitative studies have focused on seagrass fish communities occurring off the seaward (south) shores of the Florida Keys. Springer and McErlean (1962) investigated fish assemblages of shallow seagrass (*Thalassia testudinum* and *Halodule wrightii*) beds off Lower Matecumbe Key. Their analysis of seasonal variation revealed an increase in both numbers of species and individuals during summer and fall. They also found that a surprisingly large number (about one-third) of the 62 species recorded were present *only* as juveniles. Thus, they emphasized the role of this habitat as a nursery area.

Alevizon and Gorham (1989) conducted an extensive visual survey of fishes inhabiting the so-called "sand plain" areas of the Looe Key National Marine Sanctuary located off Big Pine Key. This area consists of a calcareous sand substratum supporting patches of seagrass of variable density. Although a total of 56 species were observed over the 24-month course of the study, they found that the diurnal fish community was largely dominated by only four labrid species. Most fishes were observed in association with seagrass areas rather than with sand patches. Additionally, they noted strong seasonal variation in population densities of both adult and juvenile fishes. This finding contrasts with that of Weinstein and Heck (1979) who found that for Panamanian seagrass fish communities, seasonal differences in species composition and abundance within particular sites were negligible.

Mangroves. Mangroves are a conspicuous component of the entire South Florida region, comprising an estimated area of around 200,000 ha of coastal and estuarine habitat (Odum et al. 1982). It is primarily the red mangrove *Rhizophora mangle* that forms fringing forests along the outer perimeter of protected shorelines and islands (see **Chapter 4**). These have a prop root system providing a distinctive habitat for fishes (Thayer et al. 1987). Although mangroves for the seaward shoreline of the Florida Keys undoubtedly constitute an important habitat for inshore fishes, there are no published descriptions of these fish assemblages. The only qualitative studies of fish assemblages intimately associated with the mangrove prop root habitat are from the estuarine waters of the Everglades (Thayer et al. 1987). These studies are discussed later in this chapter in the section dealing with that environment.

Sand Flats. A large portion of the inshore marine environment of South Florida is composed of expanses of calcareous sand. These appear to be relatively barren areas for fishes, offering little in the way of shelter or food. Because of these qualities, sand flats have received almost no attention from ichthyologists. Nonetheless, there are fishes that are residents of these areas (**Table 7.1**). Personal observations suggest that these are generally small cryptic forms as well as postlarvae and juveniles of reef- dwelling species which take advantage of various topographic discontinuities and structures as shelters. Shells, coral rubble, and the like, often have a tiny assemblage of small fishes associated with them. There are also burrowing forms (e.g., gobies, jawfish, tilefish, eels, etc.) that find shelter in the substrate (Bohlke and Chaplin 1968). A few species (most notably gerreids) are frequently observed swimming freely over these sand areas. Unfortunately, there are no published analyses of this interesting segment of the inshore fish fauna of the South Florida region.

Offshore Habitats

The offshore waters of the Straits of Florida proper include the remaining habitats considered in this section. This is an unusually complex offshore marine environment. Devaney (1969) noted that, "Geographically and oceanographically the Straits are unique since a major current is impinged within a narrow funneling channel between the North

American continent on one side and the Bahamian Platform and Cuba on the other." He defined three ecological zones on a bathymetric basis: the epipelagic, mesopelagic, and bathypelagic. However, in reference to these zones, he pointed out that each must be environmentally defined at different areas of the Straits, because the atypical hydrography and unusual topography of the region makes traditional bathymetric definitions of these zones inapplicable. Devaney (1969) concentrated on the Myctophidae (lanternfishes). While these typically dominate deepwater fish faunas, they are not the only fishes inhabiting these areas. Unfortunately, little additional information is available.

The epipelagic waters of the Straits of Florida offshore the Florida Keys are of particular interest because (1) they support a large sport fishery, and (2) they are the "highway" travelled by many planktonic larval fishes that eventually settle and recruit to the reefs and other inshore areas of South Florida (see **Chapter 6**). The sport fishery aspects of these waters are discussed later in this chapter by Bannerot. Major families inhabiting this zone are Carangidae (jacks), Coryphaenidae (dolphins), Exocoetidae (halfbeaks and flyingfishes), Istiophoridae (billfishes), and Scombridae (mackerels). Such fast swimming, active surface fishes are particularly sensitive to changes in water quality, especially turbidity and dissolved oxygen. Oxygen is critical to their high metabolic demands as a result of elevated swimming rates. Thus, they are far less tolerant than most fishes of lowered oxygen concentrations, increased carbon dioxide levels, sediments, or other substances that might chemically or mechanically interfere with gas transport across their sensitive gill membranes (Marshall 1966; Lagler et al. 1977). Additionally, because these species are primarily visual predators, good water clarity is essential (Moyle and Cech 1988).

Regarding ichthyoplankton, there is a growing body of literature suggesting that at least some, if not many, reef fishes may be limited in abundance, chiefly through the supply of available larval recruits (Williams 1980; Yoshioka 1982; Doherty 1983; Victor 1983; Wellington and Victor 1985). In this context, it is worth noting that Lobel (1989) summarized evidence suggesting that some reef fishes apparently time spawning to maximize return of larvae via currents. In the waters of the Straits of Florida, a persistent current structure "provides a mechanism for the retention of lobster and fish larvae produced locally in the coastal and nearshore waters of the Lower and Middle Florida Keys, and also a preferred region for onshore transport of larvae from upstream remote source regions" (Lee 1988).

These studies all suggest that there is a close link between larval transport in these offshore waters and the fish community structure of inshore reef areas. Larval fishes in general are very sensitive to water quality, as evidenced by the difficulties of attempting to raise them under controlled conditions. Thus, the stability of reef fish communities of South Florida appears to be dependent to some degree upon the continued high water quality characteristic of the epipelagic zone of the Straits of Florida. Also, Dooley (1972) sampled the ichthyofauna associated with floating *Sargassum* in the Florida Current, and found 54 species. He concluded that rafting in *Sargassum* played a major role in the life history of many fishes that inhabit inshore benthic areas as adults, by providing food and shelter in the open ocean waters.

The deep, benthic fish assemblages of the Straits of Florida have been investigated by using an extensive series of bottom trawls. Steiger (1970) analyzed and summarized the results of this sampling program which revealed a surprising diversity of fishes, including 189 species, representing some 58 families. These figures represent the fauna of the Straits as a whole, and not all of these are included in that portion of the Straits encompassed by this document. According to Steiger's division, the geographic units most applicable in the context of this paper are most of the central and a portion of the southern Straits. He also discussed the history of biological exploration of the Straits,

the geographic and bathymetric distributions of each species, and analysis of assemblage distribution patterns.

Florida Bay

Florida Bay, which includes the Everglades estuary, represents a vast (>1,500 km^2) estuarine system, receiving its freshwater drainage from the South Florida mainland via natural drainage as well as human-made canals. It grades into a fully marine environment toward the Keys to the south and toward the Southwest Florida shelf to the west. Benthic vegetation includes seagrasses (primarily *Thalassia testudinum* and *Halodule wrightii*) and algae (*Penicillus* spp.).

The fish fauna of both the estuarine and marine portions of this environment differs substantially from the nearby tropical marine fauna discussed in the previous sections. As Rosseler (1970, p. 863) pointed out, "The Everglades estuary derives its fish fauna from the fishes of the temperate Gulf of Mexico, rather than from the tropical insular fauna of the Florida Keys." In general, this statement can be extended to include most of Florida Bay and the eastern Gulf of Mexico including the shore fishes through the Cape Sable area (Carter et al. 1973; Schmidt 1979; Sogard et al. 1987; Thayer et al. 1987).

The aquatic environment is characteristically continental in this area, with relatively high turbidity, primarily silt or mud substrates, and an absence of reefs, or reef-like habitats. Structural relief throughout most of the area is provided only by the natural bottom topography, and macrofloral communities (mangroves).

The shallow-water fish fauna of this region has been reasonably well studied, and predictably is dominated by characteristically continental families: Engraulidae (anchovies), Gerreidae (mojarras), Lutjanidae (snappers), Mugilidae (mullets), Sciaenidae (drums), Sparidae (porgies), etc. (Carter et al. 1973; Thayer et al. 1987) (**Table 7.1**). As would also be predicted for a primarily continental fauna, the species diversity is substantially lower than that of the insular fauna.

Studies of the fishes of this region date back to the last century. Early descriptive studies include those of Lonnberg (1894) and Henshall (1891). Recent quantitative studies begin with that of Tabb and Manning (1961) who surveyed fishes of the Everglades National Park. Roessler (1970) found 103 species representing 43 families in Buttonwood Canal (Everglades National Park). He also discussed seasonal variability in abundances, effects of tides on relative abundance of species in samples, and the effects of temperature and salinity on sample results. Hudson et al. (1970) surveyed the fishes inhabiting a basin in south-central Florida Bay.

More recent comprehensive studies on the estuarine fishes of Florida Bay include those of Carter et al. (1973), Lindall et al. (1973) and Harmic et al. (1974), all of whom used both trawl and seine collections, resulting in a more thorough sampling of the fishes of the region. Carter et al. (1973) investigated a variety of estuarine habitats in the Ten Thousand Islands area. They found 134 species, dominated by the same fishes reported as dominants from other areas of the Southwest Florida coast (Gunter and Hall 1965; Roessler 1970; Wang and Raney 1971). Many popular sportfish were found to use the area as nursery grounds, including red drum, snook, grey and lane snappers, sheepshead, tarpon, and spotted seatrout.

Schmidt (1979) conducted a comprehensive, 40-month study of the fishes of Florida Bay, as well as examined a variety of ecological parameters associated with their

distribution and abundance patterns. Using seines and otter trawls at 27 stations, he noted almost 200,000 fishes, representing 128 species and 50 families. He found that dominant species varied greatly among different subhabitats. Salinity appeared to be the major environmental factor influencing fish distributions, and a distinct seasonal component was present regarding general distribution and abundance patterns of individual species, as well as overall biomass and community structure. In summary, he also emphasized the strong faunal affinities of the region with the temperate fish faunas of the northern Gulf of Mexico and the west coast of Florida.

Thayer et al. (1987) investigated juvenile fish communities from a variety of habitats in the Everglades National Park. They collected over 90 species, although only 11 of these comprised over 90% of the individuals taken. They also conducted the most comprehensive investigation available to date on the fish assemblages associated with mangrove prop roots. In that study, 87 species representing 37 families of fishes were taken in and around the red mangrove. Analysis of these results revealed a higher biomass and greater fish abundance in the mangrove than in adjacent seagrass areas. They also observed a marked seasonality to fish abundance, with overall density and standing crop peaking during the fall months. Additionally, most of the dominant species were *not* the typical dominants of Florida Bay in general, indicating that this is a somewhat specialized habitat type. They concluded that mangroves must be considered a major nursery area for many fishes.

Finally, Sogard et al. (1987) developed a throw-trap method to quantify fish assemblages inhabiting seagrass beds on Florida Bay mudbanks. The higher efficiency of the sampling method resulted in an overall average fish density higher than that found in previous seagrass studies. Additionally, they found distinct fish communities within each of the four subhabitats studied.

Considerable literature also exists on the biology and ecology of some key sport fishes of this area. These include the works of Yokel (1966) on the red drum *Sciaenops ocellatus*, Croker (1962) on the gray snapper *Lutjanus griseus*, Marshall (1966) and Fore and Schmidt (1973) on the snook *Centropomus undecimalis*, and Stewart (1961) on the spotted seatrout *Cynoscion nebulosus*.

Southwest Florida Shelf

The demersal fish fauna of the Southwest Florida shelf is derived from the general ichthyofauna of the Gulf of Mexico region, but differs in dominance and abundance patterns. These differences appear to stem chiefly from differences in bottom type and topography (Darcy and Gutherz 1984). The northern Gulf of Mexico, with a few notable exceptions (e.g., Flower Garden Banks), consists primarily of mud/sand/silt substrate with little topographic relief. The Southwest Florida shelf contains a fair amount of hardground (also called live bottom), consisting of the eroded limestone base of the former reef platform. The additional relief provided by this bottom type radically alters the characteristics of the resident fish communities as compared with flat, open areas; hardgrounds tend to be dominated by typical reef-dwelling species (e.g, lutjanids, haemulids, holocentrids, etc.).

The most complete survey of demersal fishes of the region is that of Darcy and Gutherz (1984), who used trawls to sample depths ranging from 9 to 193 m. They found abundance of fishes in the Southwest Florida shelf area to be generally lower than those of more northerly areas sampled west of Tampa Bay. They also found the highest catch rates were obtained at depths ranging from 20 to 39 m, with a pronounced decline below 80 m. Thirteen families were found in inshore waters (<80 m), with

haemulids and sparids dominating. Offshore, 15 families were represented, with Myliobatidae (eagle rays) and Bothidae (lefteye flounders) dominating.

The only other ichthyological survey of this area worth noting was that of Juhl (1966). Although the results of that survey and the work of Darcy and Gutherz (1984) are in general agreement on species composition, there were notable differences in the results of the two studies in a quantitative sense. These differences are almost certainly attributable mainly to differences in methodology (i.e., gear types) (Darcy and Gutherz 1984). Dominant families of this environment are listed in **Table 7.1.**

Conclusions

The fish fauna of South Florida is rich and diverse, consisting of a mixture of temperate continental and tropical insular fishes. The tropical insular component occurs seaward (south) of the Florida Keys through the Straits of Florida. This area contains a number of distinctive but highly interactive fish assemblages associated with major habitat types, including coral reefs, seagrass beds, mangroves, sand flats, and the pelagic habitats of the Straits proper.

The waters to the north of the Florida Keys include those of Florida Bay, an extensive estuarine system bordering the Everglades, as well as the Southwest Florida shelf. The fish fauna of this area is continental, derived from the temperate fauna of the northern Gulf of Mexico and closely allied with that of the West Florida coast. These waters also contain a variety of habitat types, including benthic macroflora (seagrasses and macroalgae), mangroves, hardgrounds, and mud/silt substrates.

While the overall composition of the fauna, its habitat distribution, and aspects of the biology of many key species are well known, there remain many gaps in our understanding of the fishes of this region. Notable exceptions include Bohnsack's (1982) experimental work on the effects of predator removal on reef fish community structure, and the study by Sogard et al. (1987) of biotic and physical factors affecting community structure of seagrass fishes. Nonetheless, most research on multi-species assemblages has consisted of simple baseline resource inventories. Perhaps most striking is the lack of studies aimed at understanding the dynamic processes that structure and maintain these assemblages. Investigations of this nature would necessarily entail multi-disciplinary, long-term (10 to 20 year) studies--not only of the fishes of a particular habitat, but of the entire food webs and nutrient cycles of which they are a part. Also badly needed are studies aimed at understanding the interaction of resident fish assemblages among various habitats. We know almost nothing regarding the transfer of materials and energy between these so-called communities. Other facets of community function, such as the complex processes involved in larval recruitment, are also vital.

Such studies are the logical next step in understanding fish communities of South Florida. Descriptive studies still have a proper and valuable place in ichthyological research. Nonetheless, they need to be accompanied to a greater degree than has occurred in the past by experimental studies aimed at understanding the underlying processes determining the observed distribution and abundance patterns of fishes of this region.

FISHERIES BIOLOGY

Scott P. Bannerot

Introduction

The study area encompasses a wide variety of subtropical and tropical fish assemblages, as described above. Estuarine communities prevail in the relatively turbid, nearshore waters of the Ten Thousand Islands, Cape Sable, and northern Florida Bay, closely juxtaposed to more tropical assemblages in the mangrove shorelines and seagrass beds of southern Florida Bay and the Florida Keys. Fish communities offshore become less continental, featuring highly diverse assemblages more comparable to the insular fauna typical of tropical oceanic islands. The offshore area is largely inhabited by tropical pelagic species with broad, often circumtropical distributions. Schooling coastal pelagic species occur seasonally as they migrate along the continental shelf. Several important invertebrate resources inhabit nearshore and offshore benthic communities. The result is perhaps one of the more diverse suites of fishery resources to be found in any area of similar dimensions in the world.

The purpose of this section is to describe these resources from the perspective of fisheries biology, including (1) the species exploited; (2) the nature of exploitation; and (3) the interaction of biological characteristics of the exploited resources with human utilization. The goal is to describe the current state of our understanding and to identify the information necessary to enhance it. Within this framework, five resource categories will be discussed: (1) inshore fishes; (2) reef fishes; (3) coastal pelagic fishes; (4) pelagic fishes; (5) invertebrates.

Much is known about some species from each of these five categories. One category of literature describes systematics. Others document highly specific aspects of, for example, distribution, physiology, food habits, reproduction, tag returns of small numbers of individuals, or behavioral observations. Much of this work, while important from other perspectives, has little relevance to stock assessment--that part of fisheries biology that investigates the biological status of exploited resources, which is most critical to management. Even a cursory description of this literature would exceed the dimensions of this chapter, as would even brief mention of much of the groundwork for stock assessment--studies on age and growth, mortality, fecundity, stock definition, and recruitment. Therefore, in the following sections, most of the references cited will be broad-based works with a direct bearing on stock assessment.

This section does not include any fishery statistics (landings and value). See **Chapter 11** for that information.

Fishery Categories

Inshore Fishes

Inshore fishes are species commonly exploited in the relatively shallow areas (usually <10 m depth) of the eastern Gulf of Mexico, Florida Bay, and nearshore [usually <5.6 km (3 nmi) from the nearest shoreline] waters of the Florida Keys. Often these are members of the earlier described estuarine, mangrove, or seagrass bed fish communities for at least part of the year. Most are predators near the top of the food web.

Table 7.2 lists the major recreationally or commercially important species. These fish are either target species of directed effort or frequent components of incidental catch. Although the table includes 39 species belonging to 16 different families, it is by no means an exhaustive listing of inshore fish species caught in the region.

Table 7.2. Fish species important to recreational (R) and/or commercial (C) fisheries in the inshore waters of the study area.

Scientific Name	Common Name	Fishery R	Fishery C
Albulidae	**bonefishes**		
Albula vulpes	bonefish	x	
Ariidae	**sea catfishes**		
Arius felis	hardhead catfish	x	
Bagre marinus	gafftopsail catfish	x	
Carangidae	**jacks and pompanos**		
Caranx bartholomaei	yellow jack	x	
C. crysos	blue runner	x	
C. hippos	crevalle jack	x	x
Trachinotus carolinus	Florida pompano	x	x
T. falcatus	permit	x	
Carcharhinidae	**requiem sharks**		
Carcharhinus brevipinna	spinner shark	x	
C. leucas	bull shark	x	
C. limbatus	blacktip shark	x	
Galeocerdo cuvieri	tiger shark	x	
Negaprion brevirostris	lemon shark	x	
Centropomidae	**snooks**		
Centropomus undecimalis	snook	x	
Elopidae	**tarpons**		
Elops saurus	ladyfish	x	
Megalops atlanticus	tarpon	x	
Haemulidae	**grunts**		
Haemulon aurolineatum	tomtate	x	
H. plumieri	white grunt	x	
H. sciurus	bluestriped grunt	x	
Lutjanidae	**snappers**		
Lutjanus analis	mutton snapper	x	
L. apodus	schoolmaster	x	
L. griseus	gray snapper	x	x
L. synagris	lane snapper	x	
Mugilidae	**mullets**		
Mugil cephalus	striped mullet		x
M. curema	white mullet		x
M. gaimardianus	redeye mullet		x
M. trichodon	fantail mullet		x
Rachycentridae	**cobia**		
Rachycentron canadum	cobia	x	x
Sciaenidae	**drums**		
Cynoscion nebulosus	spotted seatrout	x	x
Pogonias cromis	black drum	x	
Sciaenops ocellatus	red drum	x	
Scombridae	**mackerels**		
Scomberomorus maculatus	Spanish mackerel	x	x
Serranidae	**groupers**		
Epinephelus itajara	jewfish	x	x
E. morio	red grouper	x	x
Mycteroperca microlepis	gag	x	x
Sparidae	**porgies**		
Archosargus probatocephalus	sheepshead	x	
Sphyraenidae	**barracudas**		
Sphyraena barracuda	great barracuda	x	
Sphyrnidae	**hammerhead sharks**		
Sphyrna mokarran	great hammerhead	x	
S. tiburo	bonnethead	x	

The inshore fishes of South Florida and the Florida Keys were exploited by the Calusa Indians for nearly two thousand years prior to the 20th century (Brookfield and Griswold 1949). Commercial and recreational fisheries were well established by the 1920s (Schroeder 1924; Endicott 1925; Munroe and Gilpin 1930). Target species have changed little, although recent (1985) elimination of commercial fishing in Everglades National Park has significantly reduced mortality rates of some traditionally caught species (Tilmant 1989).

Inshore commercial fisheries have concentrated primarily on catching mullet (mostly striped and white), Florida pompano, and Spanish mackerel with gill and trammel nets. Some gill netting of gray snappers occurs in the Middle and Lower Keys. Gray snappers, crevalle jack, spotted seatrout, and sheepshead are among the marketable incidental catch of the net fisheries (Tilmant 1989). Snook and red drum have been closed to commercial fishing in Florida (Florida Marine Fisheries Commission [FMFC] 1989). These and other conservation measures (closed areas and seasons, bag limits, size limits, gear limitations--see FMFC 1989), in recognition of the unique recreational value of those resources, has largely curtailed inshore commercial effort in the region.

Recreational hook-and-line fisheries are now responsible for the majority of fishing mortality experienced by inshore fish populations, although the previously mentioned regulations have also reduced and controlled this mode of fishing effort. The inshore recreational fishery consists of two main components, professionally guided trips and trips by private boats, with fishing from shore, piers, and bridges comprising most of the remaining effort (Rockland 1988). Spearfishing is prohibited in State waters from Long Key northward along the Keys, and is not feasible due to turbidity and lack of legal prey through the Ten Thousand Islands and much of northern Florida Bay.

Bonefish, tarpon, and permit are primary targets of professionally guided trips. Bonefish and permit are available year round, while greatest abundances of tarpon in the area occur between April and July. These are essentially non-kill fisheries, except for occasional retention of trophy-sized individuals for mounting or tournament weigh-ins. The recent State requirement of a $50 license to kill a tarpon has sharply reduced the previously low fishing mortality for this species (W. Fox, pers. comm. 1989, FMFC). Most remaining guide effort is directed mainly at snook, spotted seatrout, and red drum, mostly during winter and early spring. Guides fish opportunistically for various sharks, groupers, Spanish mackerel, cobia, barracuda, and snappers, particularly gray snappers.

Private boats and shore fishermen target most of the same species as the guides. The emphasis, however, is on more easily captured, edible fish. Tilmant (1989) described the private recreational fishery operating in Everglades National Park, stating that the most popular target species were spotted seatrout and red drum. Snappers and grunts are popular targets of boat and shore fishermen further south in the less estuarine areas of the Florida Keys. A proportion of private effort is more specialized, with equipment and target species nearly identical to professional guides.

Recent studies have described the biological status of some of the more heavily exploited species in **Table 7.2.** Perhaps the best data base and most comprehensive analyses exist for red drum [U.S. Department of Commerce (USDOC) 1986; Gulf of Mexico Fishery Management Council (GMFMC) 1987; Goodyear 1989). The recent surge in the popularity of red drum as restaurant fare has stimulated the rapid growth of commercial net fishing throughout the Gulf of Mexico, causing concern that reduced numbers of spawning stock and increased fishing for juveniles may be depressing recruitment below adequate levels. Tilmant et al. (1989) suggested declines in the fishable population in the Florida Bay area. Stringent regional management by both State and Federal agencies was recommended and has been adopted in the past two years (FMFC 1989; Goodyear 1989).

Unlike red drum, spotted seatrout spend their entire life within the estuarine system of South Florida, with possible separable populations in Florida Bay and adjacent eastern Gulf of Mexico nearshore areas (Rutherford et al. 1989a). Numbers of adults are believed to have fluctuated over the past 15 years, which is typical of other estuarine fishery resources, but are currently stable at a sustainable level. Rutherford et al. (1989b) also did work on aspects of the population dynamics of gray snapper, but the results have less implications for the study area due to their wider distribution and a tendency to migrate offshore to spawn.

Similar regional work on mullet, an important food source for various recreational target species in South Florida, has been recently completed on movements (Funicelli et al. 1989) and biomass (Scott et al. 1989). A comprehensive assessment nearing completion by Florida Department of Natural Resources personnel encompasses more of the migratory range and will provide insight into the biological status of the stock (W. Fox, pers. comm. 1989).

Relatively little is known about the population dynamics and current biological status of other popular inshore target species such as tarpon, bonefish, permit, and snook. In the absence of other sources of exogenous mortality, however, there is less pressure on government agencies to investigate the first three because of the non-kill nature of the fishery, and in the case of snook, because of present stringent regulations protecting the stock.

Reef Fishes

Reef fishes are species usually exploited in the vicinity of either well-developed coral reefs; subtropical hard bottom, which consists of lower-relief, rocky ledges with minor scleractinian coral growth, sponges, and octocorals; or natural or artificial bottom structures. Reef fisheries usually occur in depths <40 m within the study area, with some exploitation of deeper-dwelling species to 200 m depth. Much of the activity occurs more than 5.6 km (3 nmi) from shore, often along the offshore edge of the Florida Reef Tract. Considerable effort is expended in the vicinity of wrecks, obstructions, and rocky projections offshore (referred to as humps), and other irregular bottom topography. Some fishing is done near shallow patch reefs (6 m depth or less) inshore of the edge of the Reef Tract.

The fish communities associated with coral reefs and offshore benthic habitats, described earlier in this chapter, encompass many of the species included in this subsection. **Table 7.3** lists reef fish species important to recreational and/or commercial fisheries off South Florida. The list includes 68 species belonging to 13 families, reflecting the high species richness and diversity typical of tropical and subtropical biological communities. Over half of the species listed are benthic, habitat-dependent snappers, groupers, grunts, and porgies. Others reside in reef areas more temporarily. All are captured largely by hook-and-line, except the halfbeaks and flyingfishes, which are caught with encircling nets for the bait industry.

Other than early artisanal efforts, the first known significant reef fish fishery within the study area was initiated by fishermen who came from New England. They fished commercially for snappers and groupers off Key West in the 1830s (Klima 1976). Commercial effort has persisted from that time, using hand lines, and more recently electric and hydraulic reels, bottom longlines, divers with spears and powerheads, and fish traps. Recreational effort, however, judging from early accounts of fishing in South Florida, seems to have developed relatively later for reef fishes than for some other nearshore fisheries.

Table 7.3. Reef fish species important to recreational (R) and/or commercial (C) fisheries in the study area.

Scientific Name	Common Name	Fishery	
		R	C
Balistidae	**triggerfishes**		
Canthidermis sufflamen	ocean triggerfish	x	
Carangidae	**jacks and pompanos**		
Alectis ciliaris	African pompano	x	
Caranx bartholomaei	yellow jack	x	
C. crysos	blue runner	x	
C. hippos	crevalle jack	x	
Seriola dumerili	greater amberjack	x	x
S. rivoliana	almaco jack	x	
Carcharhinidae	**requiem sharks**		
Carcharhinus leucas	bull shark	x	x
C. obscurus	dusky shark		x
C. plumbeus	sandbar shark	x	x
Galeocerdo cuvieri	tiger shark	x	x
Negaprion brevirostris	lemon shark	x	x
Exocoetidae	**halfbeaks and flyingfishes**		
Cypselurus sp., *Exocoetus* sp.	flyingfish		x
Hemiramphus balao	balao		x
H. brasiliensis	ballyhoo		x
Haemulidae	**grunts**		
Haemulon album	margate	x	x
H. aurolineatum	tomtate	x	x
H. flavolineatum	French grunt	x	x
H. melanurum	cottonwick	x	x
H. plumieri	white grunt	x	x
H. sciurus	bluestriped grunt	x	x
Labridae	**wrasses**		
Lachnolaimus maximus	hogfish	x	x
Lutjanidae	**snappers**		
Apsilus dentatus	black snapper	x	x
Etelis oculatus	queen snapper	x	x
Lutjanus analis	mutton snapper	x	x
L. apodus	schoolmaster	x	x
L. buccanella	blackfin snapper	x	x
L. campechanus	red snapper	x	x
L. cyanopterus	cubera snapper	x	x
L. griseus	gray snapper	x	x
L. mahogoni	mahogany snapper	x	x
L. jocu	dog snapper	x	x
L. synagris	lane snapper	x	x
L. vivanus	silk snapper	x	x
Ocyurus chrysurus	yellowtail snapper	x	x
Rhomboplites aurorubens	vermilion snapper	x	x
Malacanthidae	**tilefishes**		
Caulolatilus microps	blueline tilefish	x	x
Lopholatilus chamaeleonticeps	golden tilefish	x	x
Malacanthus plumieri	sand tilefish	x	
Scombridae	**mackerels and tunas**		
Euthynnus alletteratus	little tunny	x	
Scomberomorus cavalla	king mackerel	x	x
S. regalis	cero mackerel	x	x
Serranidae	**groupers**		
Epinephelus adscensionis	rock hind	x	x
E. cruentatus	graysby	x	
E. drummondhayi	speckled hind	x	x
E. flavolimbatus	yellowedge grouper	x	x
E. fulvus	coney	x	
E. guttatus	red hind	x	x
E. itajara	jewfish	x	x
E. morio	red grouper	x	x
E. mystacinus	misty grouper	x	x
E. nigritus	Warsaw grouper	x	x
E. niveatus	snowy grouper	x	x
E. striatus	Nassau grouper	x	x
Mycteroperca bonaci	black grouper	x	x
M. interstitialis	yellowmouth grouper	x	x
M. microlepis	gag	x	x
M. phenax	scamp	x	x
M. tigris	tiger grouper	x	x
M. venenosa	yellowfin grouper	x	x
Sparidae	**porgies**		
Calamus arctifrons	grass porgy	x	x
C. bajonado	jolthead porgy	x	x
C. calamus	saucereye porgy	x	x
Pagrus pagrus	red porgy	x	x
Sphyraenidae	**barracudas**		
Sphyraena barracuda	great barracuda	x	
Sphyrnidae	**hammerhead sharks**		
Sphyrna mokarran	great hammerhead	x	
S. lewini	scalloped hammerhead	x	
S. zygaena	smooth hammerhead	x	

Today, recreational fishing has a greater impact on the South Florida economy than does commercial fishing (Rockland 1988). This trend is particularly apparent in the case of the reef fishery. The recreational sector of the fishery is comprised primarily of charter boats (usually between 5.5 and 22 m length), headboats (usually between 18 to 37 m length), and private boats of virtually all descriptions. Fishing power per unit effort has increased considerably in recent years with the advent of inexpensive LORAN units and electronic depth recorders, making precise location and identification of bottom structures possible for the relatively inexperienced fisherman. Wrecks in the eastern Gulf of Mexico fished previously by a small number of guides from Marathon and Key West may now become crowded with private boats (J. Wells, pers. comm. 1989, fishing guide, Marathon, Florida). Similarly, many reef areas and wrecks off the Upper Keys known only to small numbers of mostly professional guides six to eight years ago are now often covered by private boats on any given day. Due to the habitat-dependent nature of many important reef species, the inevitable result has been increased pressure on the resource.

The biological status of most populations of exploited reef fishes is poorly known due to a particularly acute lack of appropriate empirical data. Further, conclusions from application of standard analytical techniques may be complicated by a protogynous hermaphroditic reproductive strategy in the case of groupers and hogfish, where individuals begin life as females and later transform into males (Bannerot et al. 1987). The multispecies nature of the reef fishery poses considerable complications to both procurement of data and assessment model application.

The first comprehensive assessment of reef species that included the study area was by the South Atlantic Fishery Management Council (SAFMC) (1983). A number of age and growth studies had been completed for various snappers, groupers, grunts, and porgies, along with scattered estimates of natural and fishing mortality. This allowed size limit analysis using a standard model, which eventually resulted in Federal minimum sizes for some species (see Huntsman and Waters 1987). The establishment of the FMFC shortly thereafter resulted in the imposition of somewhat more stringent size limits (particularly for groupers) in State waters, as well as bag limits (FMFC 1989). The GMFMC has now performed some analyses similar to those of SAFMC (1983) and is in the process of updating reef fish regulations.

A poorly documented, but economically significant industry in the Florida Keys is based on the capture and sale of inshore and reef fishes and invertebrates for aquaria, as well as the capture and preservation of various shelled molluscs for sale in gift shops.

Coastal Pelagic Fishes

Five coastal pelagic fish species are taken by recreational and commercial fisheries in the study area: cobia, three mackerels, and a small tuna (**Table 7.4**). These are schooling, migratory fishes available seasonally. Most are caught within 9.3 km (5 nmi) of shore in the study area except in the Gulf of Mexico west of the Middle Keys and northwest of Key West and the Lower Keys.

Table 7.4. Coastal pelagic fish species important to recreational (R) and/or commercial (C) fisheries in the study area.

Scientific Name	Common Name	Fishery	
		R	C
Rachycentridae	**cobia**		
Rachycentron canadum	cobia	x	x
Scombridae	**mackerels and tunas**		
Euthynnus alletteratus	little tunny	x	
Scomberomorus cavalla	king mackerel	x	x
S. maculatus	Spanish mackerel	x	x
S. regalis	cero mackerel	x	x

The development of the commercial coastal pelagic fisheries is summarized in Gulf of Mexico and South Atlantic Fishery Management Councils (GMSAFMC) (1985). King and Spanish mackerel are traditional targets of major commercial fisheries in South Florida. A significant king mackerel fishery existed by the early 1900s. Large-scale exploitation of Spanish mackerel was occurring by the 1920s. The two main gear types for both were hook-and-line and gillnets. During the 1960s, fishing power per unit effort increased considerably due to larger vessels, power reels for hook-and-line, power rollers for hauling gill nets, and use of electronic fish finders and spotter planes. Cobia, cero mackerel, and little tunny have traditionally been caught incidentally by commercial fishermen. Considerable commercial hook-and-line effort has occurred in recent years, however, for cobia.

The recreational fishery for coastal pelagics in South Florida has followed a similar course to that for reef fishes. While small numbers of sportsmen have exploited the resource since at least the early 1900s, major development has occurred after commercial fisheries were established. This was because small vessels became available to an increasingly large body of private recreationists through the 1950s and 1960s, culminating in the fiberglass, "open fisherman" seen most commonly today: between 5 and 12 m length, and equipped with outriggers, electronics, and multiple rod holders. The same charter boats and headboats described for reef fisheries also target coastal pelagic fishes seasonally. Recreational fishermen use hook-and-line almost exclusively for coastal pelagics.

The biological status of king mackerel is perhaps the best known of the five species in this subsection. Some information relevant to stock assessment of Spanish mackerel is available. Both species are believed to be in relatively advanced states of overfishing (GMSAFMC 1985). Little salient information is available for cobia, and almost nothing is known of the biological status of cero mackerel or little tunny.

King mackerel were divided into two separate management groups based on length frequency information, results of tagging, an index of catch per unit effort, and historical landings; these are termed the Gulf of Mexico and Atlantic migratory groups (Powers and Eldridge 1983a,b). The Gulf group is thought to be in a more advanced state of overfishing than the Atlantic group (Powers and Eldridge 1983b, GMSAFMC 1985). This group is present in the study area during the winter months (November-March), while the Atlantic group is thought to contribute most of the catch from the area during the summer (April-October). Acceptable Biological Catch is determined annually

based on landings data for each group separately, from which managers select a Total Allowable Catch, which is then allocated between the commercial and recreational user groups. The fisheries are closed at the time the respective allocations are estimated to have been caught. During the open season, gill net mesh sizes are in effect for commercial fishermen and bag limits are enforced for recreational fishermen.

Spanish mackerel are managed according to a similar strategy. Genetic differences between individuals from the Gulf of Mexico and Atlantic individuals were deemed sufficient to manage the two groups separately (GMSAFMC 1985). Within the study area, the Gulf group contributes virtually all of the catch year round. In addition to quotas and bag limits, a minimum size is in effect for Spanish mackerel. State regulations are similar to Federal regulations for both king and Spanish mackerel, except that the State has deferred from king mackerel season closures the past two years (FMFC 1989).

Cobia are caught in the vicinity of wrecks in the eastern Gulf of Mexico within the study area and as they migrate in schools along the shallows of the Florida Reef Tract during the spring months. Their stock structure is poorly known, although some information suggests separate Atlantic and Gulf groups. At present, both a minimum size and a daily bag limit are in effect.

Pelagic Fishes

This subsection includes fishes commonly exploited in the open waters of the Straits of Florida offshore of the Reef Tract. **Table 7.5** lists the important species for the study area. Most are migratory and therefore more abundant at particular times of the year. Nineteen species from six families are listed. All are billfish, dolphin, swordfish, sharks, or members of the tuna family.

SAFMC (1985, 1988) summarized aspects of the history of exploitation. Within the study area, the traditional offshore target species were billfish and dolphin, and, to some extent, sharks. With the exception of short-lived commercial shark fisheries in the Lower Keys in the early part of this century, the majority of effort until recently has been recreational. Recreational offshore fishing in the study area was the pursuit of a small number of wealthy anglers between 1900 and World War II, many of whom were attracted by Ernest Hemingway's written accounts of adventures in the Bahamas and Keys. Participation increased with the previously described combination of growing numbers of recreationists and the manufacture of small boats suitable for ocean fishing.

Marlin, because of their relatively low numbers in the area, are a fairly rare catch in the Florida Keys. They are targeted primarily in the summer months by charter boats or private offshore fishing yachts after sufficient catches of other species, especially dolphin, are made. Most smaller private boats target more abundant, more easily caught species such as dolphin, and, to a lesser extent, blackfin tuna, skipjack tuna, little tunny, and wahoo. Sailfish and larger blackfin tuna are available in winter and early spring months in sufficiently large numbers to allow directed charter and private fishing yacht effort and a growing amount of effort from the smaller offshore private boats.

Table 7.5. Pelagic fish species important to recreational (R) and/or commercial (C) fisheries in the study area.

Scientific Name	Common Name	Fishery R	Fishery C
Carcharhinidae	**requiem sharks**		
Carcharhinus falciformes	silky shark	x	x
C. leucas	bull shark	x	x
C. obscurus	dusky shark		x
C. plumbeus	sandbar shark	x	x
Galeocerdo cuvieri	tiger shark	x	x
Coryphaenidae	**dolphins**		
Coryphaena hippurus	dolphin	x	x
C. equisetis	pompano dolphin	x	
Istiophoridae	**billfishes**		
Istiophorus platypterus	sailfish	x	
Makaira nigricans	blue marlin	x	
Tetrapturus albidus	white marlin	x	
T. pfluegeri	longbill spearfish	x	
Lamnidae	**mackerel sharks**		
Carcharodon carcharias	white shark	x	
Isurus oxyrinchus	shortfin mako	x	x
I. paucus	longfin mako	x	x
Scombridae	**tunas and wahoo**		
Acanthocybium solanderi	wahoo	x	x
Euthynnus alletteratus	little tunny	x	
Thunnus albacares	yellowfin tuna	x	x
Thunnus atlanticus	blackfin tuna	x	x
Thunnus thynnus	bluefin tuna	x	x
Sphyrnidae	**hammerhead sharks**		
Sphyrna lewini	scalloped hammerhead	x	
S. mokarran	great hammerhead	x	
S. zygaena	smooth hammerhead	x	
Xiphiidae	**swordfish**		
Xiphias gladius	swordfish	x	x

Commercial offshore fishing in the southern Straits of Florida has consisted primarily of longlining for swordfish. The fishery began with effort by Cuban-American fishermen in small vessels off Miami in the early 1970s (Berkely 1981), followed by a rapid expansion of larger boats and more advanced gear through the early 1980s until depressed catches induced fishermen to go elsewhere (SAFMC 1985). Charter boats entered the fishery briefly, fishing with rod and reel at night in the late 1970s until plummeting catch rates discouraged further effort. Some swordfish longlining continues in the Straits of Florida, particularly off Key West in the winter months.

Sharks are a common bycatch of swordfish longlines, and are retained for market, depending on size and species. Most mako sharks are retained due to their consistently high market value. There is at least one commercial shark longline operation in the Upper Keys. Sharks are also exploited by charter boats off the Keys, both selectively and opportunistically. In particular, directed effort for mako sharks occurs during the spring when they are available in the vicinity of offshore humps, the rocky projections rising from the ocean floor in the Straits of Florida.

The biological status of pelagic fishes that are important to fisheries in the study area as they pass through is in general poorly known. Elsewhere in their range, marlin, and in some areas sailfish, are thought to experience considerable mortality as bycatch

of foreign and domestic tuna and swordfish longline operations. Recently, in a joint plan, the regional Fishery Management Councils have made possession of billfish illegal for longliners, the sale of billfish illegal for anyone, and imposed minimum sizes for recreational anglers except in the case of longbill spearfish (SAFMC 1988). The State has imposed a limit of one billfish per person per boat trip for recreational anglers (FMFC 1989).

The status of swordfish stocks has been the best studied of the species in this subsection. These efforts are summarized in SAFMC (1985) and most recently updated by USDOC (1989a). The population is thought to be severely overfished at present. The Fishery Management Councils have decided to undertake strong regulatory action to rebuild the stock (USDOC 1989b).

Tunas in the U.S. Exclusive Economic Zone are currently managed under the Magnuson Act. There are no State regulations governing tuna, although there is some support developing to change this situation (Russell 1989). The larger species present, yellowfin and bluefin, are not caught in significant numbers in the study area. An intensive longline fishery for yellowfin tuna operates in other areas of the Gulf of Mexico (Wilson 1988). Also, bluefin tuna spawn in contiguous waters of the Gulf of Mexico, and their larvae have been recorded in the vicinity of the study area (Richards et al. 1981; McGowan and Richards 1986). The bluefin population is thought to be in an extreme state of overfishing (see Russell 1989). Virtually nothing is known, however, about the population status of the smaller blackfin tuna, skipjack tuna, and little tunny commonly caught off the Florida Keys. The same is true of dolphin, the most common target of summer offshore recreational fishing in the Keys, wahoo, and requiem sharks, the most frequently landed offshore sharks.

Invertebrates

Table 7.6 lists invertebrate species important to fisheries in the study area. Spiny lobster, pink shrimp, and stone crab are subjected to intensive commercial effort. All three are also sought by recreationists, particularly spiny lobster, Blue crab and spotted lobsters are taken opportunistically in significant numbers by both commercial and recreational fishermen. Smooth-tailed, Spanish, and slipper lobsters are caught less frequently. Not listed in the table is queen conch (*Strombus gigas*), which previously was important to nearshore fisheries in the area. Because of severe depletion of local populations due to overfishing, a moratorium is in effect on all fishing for queen conch.

Table 7.6. Crustacean invertebrates important to recreational (R) and/or commercial (C) fisheries in the study area.

Scientific Name	Common Name	Fishery R	Fishery C
Palinuridae	**spiny lobsters**		
Panulirus argus	spiny lobster	x	x
P. guttatus	spotted lobster	x	
P. laevicauda	smooth-tailed lobster	x	
Penaeidae	**shrimp**		
Penaeus duorarum	pink shrimp	x	x
Portunidae	**swimming crabs**		
Callinectes sapidus	blue crab	x	x
Scyllaridae	**slipper lobsters**		
Scyllarides aequinoctialis	Spanish lobster	x	
S. nodifer	slipper lobster	x	
Xanthidae	**benthic crabs**		
Menippe mercenaria	stone crab	x	x

Four invertebrate species are discussed below: spiny lobster, pink shrimp, stone crab, and queen conch.

Spiny Lobster. During the day, adult spiny lobsters reside primarily under ledges, in holes and crevices in coral reefs, and in other natural and artificial bottom structures featuring similar enclosures. Within the study area, reproductively active adults occur mostly on the Reef Tract to the south and east of the Florida Keys, and in the deeper channels and waters of Florida Bay and the Gulf of Mexico west of the Keys. Daytime congregations disperse over adjacent seagrass, algal, and sand flats to feed at night (Herrnkind et al. 1975). Spawning takes place at these offshore locations (Menzies and Kerrigan 1980), with peak activity in spring and early summer. Female lobsters retain larvae for one to two weeks before releasing them to currents that transport them to the epipelagic zone of the open ocean. The phyllosome transits 10 to 12 stages over an estimated 6 to 12 months in this environment before metamorphosis to the puerulus stage, which then takes up a benthic existence in shallow, nearshore waters (Herrnkind and Butler 1986). Marx and Herrnkind (1986) give a detailed account of the habitat requirements of this and subsequent juvenile stages. At 17 to 20 mm carapace length, juveniles abandon algal clumps for den-like habitats. Larger juveniles begin movement to the offshore areas favored by adults (Lyons et al. 1981).

GMSAFMC (1982, 1989) reviewed the history of the spiny lobster fishery in South Florida. Significant landings have been recorded from the earliest catch statistics available for the area. Most were either consumed locally or used for bait in the early 1900s (Schroeder 1924), with subsequent increases in commercial effort commensurate to advances in freezer facilities and refrigerated distribution systems through the 1960s. Traps remain the primary commercial gear. A small percentage of the commercial catch and much of the recreational catch comes from divers using tickler sticks, hand nets, and their hands. Landings peaked in the 1970s, but were inflated by American commercial boats fishing in Bahamian waters. Upon closure of the Bahamas to the American lobster fleet in 1975, landings declined initially and have remained relatively stable since.

The stability of the spiny lobster fishery was not expected by most scientists due to the high degree of overcapitalization, particularly in the past 15 years, and geographic limitation (essentially the Reef Tract and limited adjacent areas) of the fishery. Most legal size adults are removed from the area during the August-March fishing season, except within the Everglades National Park and Biscayne Bay-Card Sound sanctuaries. Considerable indirect evidence supports the hypothesis that at least some proportion of recruitment is via larval drift from the Caribbean (Lyons 1980, 1986).

Lyons (1986) reviewed current detriments to productivity and maintenance of the spiny lobster fishery, concluding that mortality through the use of sublegal size lobsters as attractants in traps, harvest in some nursery areas, and lack of escape gaps in traps contribute to suboptimal production. Herrnkind et al. (1988) provided evidence that siltation of critical habitat can negatively influence postlarval settlement. Several contributions, summarized by Marx and Herrnkind (1986), emphasize the pristine oceanic conditions required by the phyllosome larval stages.

Pink Shrimp. Pink shrimp, and outside the study area, brown shrimp (*Penaeus aztecus*) and white shrimp (*P. setiferus*), contribute to a large, diverse commercial fishery that operates throughout the Gulf of Mexico; these shrimp species are among the most important fisheries in the Nation. A concentration of the deeper-dwelling royal red shrimp, *Peloticus robustus*, is known to exist off the edge of the continental shelf in water depths of 280 to 600 m, south-southeast of the Dry Tortugas in the Straits of Florida (GMFMC 1981).

Like spiny lobsters, adult pink shrimp are most abundant farther from shore than the juvenile stages. Adult pink shrimp prefer calcareous sand bottoms in waters between 9 and 44 m deep (Kutkuhn 1962). Spawning occurs throughout the year. The pelagic larvae undergo 10 to 13 stages over approximately a two-week period as they are transported by currents from offshore to the inshore estuarine nursery grounds. Here, the postlarvae assume a benthic existence, becoming juveniles during the 2- to 6-month stay inshore, after which they migrate to offshore waters at season- and area-specific sizes (Bielsa et al. 1983).

Two major pink shrimp grounds occur off Southwest Florida: the Tortugas grounds, located in the study area, and the Sanibel grounds, which is to the north of the study area (GMFMC 1981; Klima et al. 1986). The primary commercial gear is a type of double-trawl developed in the late 1950s. Single otter trawls, introduced in the early 1900s, and haul seines were the previous primary gear. Small-scale commercial bait shrimpers still use single otter trawls. Recreational shrimpers use lanterns and dipnets or tow fine-meshed PVC frame nets behind small boats. The primary management measure off South Florida has been areal closures within the Tortugas shrimp ground in recognition of its value to the resource. Some changes in the boundaries have occurred over the years, as well as temporary openings to fishing (USDOC 1989c). The existence of natural refugia to trawl gear, high fecundity and extended spawning, and rapid growth rates are thought to contribute to the apparent resiliency of shrimp to exploitation. Nichols (1986) updated stock assessment analyses, concluding that some increase in yield could be realized if the current target minimum size (103 mm total length) were achieved. The major concern for maintenance of the fishery is preservation of the estuarine environments critical as nursery areas for juveniles and subadults.

Stone Crab. Adult stone crabs usually inhabit dens within burrows and crevices located in channels and seagrass flats, and may at times be found on open sand bottom or oyster beds (Bert et al. 1986). Although stone crabs are found throughout coastal waters of Florida, the region of greatest abundance occurs within the study area in the Gulf of Mexico west of Cape Sable (Lindberg and Marshall 1984). Copulation occurs in the dens, with peak spawning activity between August and October. The planktonic larvae require approximately one month to pass through five or six zooeal stages, settling after metamorphosis to the postlarval megalops stage. Yang and Kratz (1976) found that these megalopae were extremely sensitive to poor water quality. Juveniles inhabit existing dead and living structures in similar areas as the adults, but they do not dig burrows.

Like the spiny lobster fishery, the fishery for stone crabs is prosecuted primarily by traps, limited geographically to a zone largely within the study area, and regulated by a closed season and minimum legal size (GMFMC 1979; Sullivan 1979; FMFC 1989), with the main difference being that all crabs must be returned to the water after claw removal. Stone crabs were recognized as a delicacy as early as the 1800s and were caught and consumed locally (Rathbun 1887). In the early 1900s, most were caught incidentally in lobster traps; only a few fishermen specialized in their commercial capture through the 1930s (GMFMC 1979). The fishery did not develop as rapidly as the spiny lobster fishery, and total number of traps in the fishery remains less than that for lobsters. Recreationists pursue stone crabs, usually capturing them by hand or with hand nets, while diving. Although the commercial fishery is important to the area, no assessment has adequately addressed the biological status of the population. The assessment by Phares (1985) was limited by imprecise data. Ehrhardt et al. (in press) addressed biological status in a limited geographical area. The major assessment complication is the inability of available models to account for variable survival rates of the crabs once they are returned to the water and rates of claw regeneration for survivors. Restrepo (1989) addressed some of these complications using a simulation

model, concluding that yield per recruit could be increased by reducing the current minimum claw size.

Queen Conch. Queen conch are large marine molluscs previously important to nearshore fisheries within the study area. They are found on a variety of firm, stable bottom types, usually those supporting macroalgae, from depths of <1 to 30 m (Brownell and Stevely 1981). Copulation and spawning activity is greatest during warmer months (Randall 1964). Egg masses are usually deposited on open sand. The veliger larvae hatch after approximately five days (D'Asaro 1965) and assume a free-swimming planktonic existence for about three weeks. Settlement is followed by metamorphosis to the postlarval stage after about one week (Brownell 1977). From this time until growth to a shell length of 6 to 8 cm, juveniles appear to spend a large proportion of time buried in the sediment (Iversen et al. 1986). Larger juveniles (up to 18 cm shell length) are found in greatest numbers in relatively shallow water (tidal flats up to <10 m depth) (Iversen et al. 1987). Mostly adults with fully formed, flared shell lips are found below 10 m depth, although these larger individuals also occur in the shallows.

Queen conch are overfished throughout much of their pan-Caribbean range, due to their accessibility and ease of capture. As noted above, populations within the study area have been severely depleted, leading to a moratorium on all fishing for queen conch.

Fishery Management Considerations

Data Required for Fishery Management

Optimal utilization of an exploited fishery resource, particularly when participation has increased beyond initial stages, normally requires management. Managers must be supplied, in the face of uncertainty, with a spectrum of options that encompass the potential problems experienced by the resource. The creation of this decision environment is the purview of the fishery biologist. This job is termed stock assessment. It consists of determining the current state of exploitation of the resource, predicting the resiliency of the population to future human utilization, and formulating a suite of regulations that allow sustained usage at a level determined to be in the best interest of user groups. The fundamental goal is to prevent depletion, defined here as a reduction in the level of abundance that would preclude realization of optimal productive capacity. The purpose of this subsection is to describe the data required for management via brief discussion of the stock assessment process, followed by a summary of data currently being collected for exploited resources within the study area.

The initial step of stock assessment should be the determination of the unit stock. This consists of the temporal and spatial demarcation of a manageable unit; ideally, an isolated, genetically distinct population or one that for practical purposes can be treated as such. This is usually done through some combination of examination of spatial distribution, distinctiveness of spawning area, features of data on catch and effort for different areas over time, age composition of catch data, results from tagging studies, and miscellaneous biological evidence (e.g., distinctive differences in genetics, morphology, physiology). This determination must normally be made on the basis of indirect or incomplete information.

Given sufficient information from one or more of the above sources, the collection of the following data for the unit stock would allow reasonably precise stock assessment: (1) total catch (in number of individuals)--by species, age, length, weight, area, depth,

and type of gear; (2) total standardized effort--by species, depth, area, and gear; and (3) fishery-independent estimates of abundance of both adults and recruits.

The next step of the stock assessment process is possible with even part of this information. This would be a preliminary examination for symptoms which may, in combination, indicate fishing rates that are causing depletion (overfishing): (1) significant declines in catch per unit effort; (2) a downward trend in total catch per annum with increasing effort; and (3) reduction in average size and age of individuals caught. Heavy overfishing may be indicated if yields are highly erratic, or if vital stock parameters change, for example a rapid decrease in age of sexual maturity.

Following preliminary examination, prediction of population response to future exogenous mortality is normally attempted by one or more of the following analytical techniques (depending on data available): (1) production models, which use a time series of catch and effort data to predict a relationship between exploitation and yield; (2) yield-per-recruit analysis, which utilizes information on age, growth, and mortality to determine if yield would increase, decrease, or remain constant if fishing rate and/or size at first capture were changed; and (3) virtual population analysis, which estimates absolute number of individuals remaining in the population by age and age-specific fishing mortality given an estimate of natural mortality, catch in numbers by age for a number of years, and estimated fishing mortality rate experienced by the oldest year class in the population. If possible, these techniques may be augmented by computer simulations of the population through time, prediction of future catch via correlation of recruitment success with environmental variables, estimated potential recruitment through surveys of pre-recruits, or a possible relationship between spawning stock size and recruitment.

Data Available for Fishery Management

Unfortunately, the collection of data sufficient for accurate stock assessment of a given fishery usually presents an overwhelming logistical problem, particularly with multi-species assemblages in a subtropical or tropical environment. The following programs currently collect information pursuant to assessment of fishery resources within the study area:

- Marine Recreational Fishery Statistics Survey (MRFSS) - initiated in 1955, this Federal data collection program estimates catch, effort, and some socioeconomic data via direct and telephone interviews. Due to various alterations and hiatuses, consistent data are available for the study area beginning in 1982.

- Charterboat Survey (CS) - attempts, via logbooks, to acquire data on catch, effort, and fish lengths from charterboat captains. Initiated by the Federal government in 1982, this program has experienced considerable difficulty and continues at present on a voluntary basis with a small number of participants. Essig et al. (1988) fully reviewed the MRFSS and the CS.

- Trip Interview Program (TIP) - attempts to collect a stratified sample of effort, catch, and fish length frequencies. TIP was initiated by the Federal government in April, 1984 from a previous program called the Creel Survey and Biological Sampling Program (CSBSP). Due to logistical problems, TIP has been of little use to stock assessment to date. Zweifel (1988) provided a recent review.

- Headboat Survey (HS) - Uses logbooks to obtain information on catch, effort, and various data necessary from individual fish for information on age, growth, and other biological information. Initiated by the Federal government (see Huntsman 1976), this program continues to provide usable data from this sector of the recreational fishery.

- Oceanic Gamefish Survey (OGS) - collects catch and effort information for billfishes by interviewing boat captains and recreational fishermen; tournaments in particular are monitored, and biological samples from individual fish are taken (see Contillo 1989). OGS was initiated by the Federal government in 1970.

- Cooperative Game Fish Tagging Program (CGFTP) - promotes tagging by recreational and commercial fishermen of billfish, tunas, tarpon, red drum, king mackerel, and other species; initiated by the Federal government in 1954 (Scott and Tashiro 1989).

- Florida Trip Ticket System (FTTS) - attempts to collect data on total commercial effort and harvest by required fish dealer reports; initiated by the State in 1984, FTTS data were considered to be fairly reliable by 1986. Bohnsack et al. (1989) provided a recent partial summary of these data.

Despite considerable effort, the previously described information needed for stock assessment remains insufficient for most fisheries within the study area. Assessments are nearly always conducted with a paucity of necessary data, increasing the uncertainty of the decision environment for fishery managers. Efforts continue, however, to improve the data base. Also, a recent trend toward implementation of conservative management measures by both the State and Federal government for a number of the diverse fishery resources within the study area may be instrumental in their preservation.

Conclusions

As discussed above, the availability of fisheries data from the study area is less than would be desired for accurate stock assessment. However, there is enough information to provide some basis for decisions regarding offshore oil and gas operations from the standpoint of fishery resources. Several observations should be taken into account in such decisions:

- The combination of continental and insular influences in the study area maintain an array of commercial and recreational fishery resources whose diversity is unparalleled in the continental U.S.

- A significant proportion of the collective resource consists of finfish and invertebrate fauna associated with the only extensive coral reef in the continental U.S.

- Another large proportion of this suite of resources is maintained by an extensive estuarine area encompassing the southern portion of the Florida peninsula.

- Offshore waters adjacent to the study area provide a documented spawning area for the severely stressed bluefin tuna, and habitat for a portion of the overfished swordfish stock.

- Many of the other fishery resources exploited within the study area, both migratory and resident species, are overfished.

Thus, the finfish and invertebrate populations of interest to humans within the study area can be described as highly diverse, geographically limited, unique, heavily utilized, and, in certain respects, ecologically sensitive. Because of the existing stress of significant fishing mortality and the myriad of less-pronounced influences resulting from juxtaposition to a large human population, additional sources of exogenous mortality could have a pronounced effect on the ability of the populations to sustain fishable levels. For example, a heavily fished finfish or invertebrate population consisting of a small number of year classes could be sharply reduced by failure of a single year's recruitment due to mass mortality of larvae caused by a pervasive change in water quality at a particular time and location. An oil spill large enough to inundate large portions of the nearshore waters of Florida Bay could significantly affect survival of both invertebrate and finfish species dependent on estuarine nursery areas (see **Chapter 15** for additional discussion of oil spill effects). Combined with existing stress from fishing, the result could be a significant reduction in population size. The effects of chronic exposure to smaller amounts of the inevitable byproducts of oil and gas development activities, while probably negative, are less certain (see **Chapter 13**). Conversely, it should be noted that existing artificial reefs in the study area attract considerable fishing effort, and that offshore drilling rigs and platforms would likely become focal points of recreational fishing as they are in the northern Gulf of Mexico. However, the addition of more artificial structures may only redistribute the standing population, not increase the biomass of sport fish in the area (Bohnsack 1989).

REFERENCES CITED

Adams, S. M. 1976. The ecology of eelgrass, *Zostera marina* (L.), fish communities. I. Structural analysis. *J. Exp. Mar. Biol. Ecol.* 22:269-291.

Alevizon, W. S., and M. G. Brooks. 1975. The comparative structure of two western Atlantic reef-fish assemblages. *Bull. Mar. Sci.* 25(4):482-490.

Alevizon, W. S., and J. C. Gorham. 1989. Effects of artificial reef deployment on nearby resident fishes. *Bull. Mar. Sci.* 44:646-661.

Alevizon, W. S., and L. E. Greene. In preparation. Temporal changes in aspects of a coral reef biota in the Florida Keys: 1974 vs. 1984.

Alevizon, W. S., and D. Landmeier. 1984. Variability in the population structures of four western Atlantic parrotfishes (Scaridae). *Environ. Biol. Fish.* 10:149-158.

Alevizon, W. S., J. C. Gorham, R. Richardson, and P. Pitts. 1985. Use of man-made reefs to concentrate snapper (Lutjanidae) and grunts (Haemulidae) in Bahamian waters. *Bull. Mar. Sci.* 37:3-10.

Anderson, G. R. V., A. H. Ehrlich, J. D. Roughgarden, B. C. Russell, and F. H. Talbot. 1981. The community structure of coral reef fishes. *Am. Nat.* 117:476-495.

Bannerot, S. P., and M. C. Schmale. 1982. Assessment of fish communities in John Pennekamp Coral Reef State Park and Key Largo National Marine Sanctuary with comments on the use of a rapid visual technique. In *Final report: An environmental assessment of the Key Largo National Marine Sanctuary*, ed. G. L. Voss.

Bannerot, S. P., W. W. Fox, Jr., and J. E. Powers. 1987. Reproductive strategies and the management of snappers and groupers in the Gulf of Mexico and Caribbean. In *Tropical snappers and groupers: Biology and fisheries management*, ed. J. J. Polovina and S. Ralston, 561-603. Boulder: Westview Press.

Berkely, S. A. 1981. *Fishery and biology of swordfish in Southeast Florida.* Manuscript prepared for Sea Grant project renewal proposal. Miami.

Bert, T. M., J. Tilmant, J. Dodrill, and G. E. Davis. 1986. *Aspects of the population dynamics and biology of the stone crab (Menippe mercenaria) in Everglades and Biscayne National Parks as determined by trapping.* Rep. No. SFRC-86/04. National Park Service, South Florida Research Center.

Bielsa, L. M., W. H. Murdich, and R. F. Labisky. 1983. *Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (South Florida). Pink shrimp.* FWS/OBS-82/11.17. U.S. Fish and Wildlife Service, Division of Biological Services.

Bohlke, J. E., and G. C. Chaplin. 1968. *Fishes of the Bahamas and adjacent tropical waters.* Wynnewood: Livingston Publ. Co.

Bohnsack, J. A. 1982. Effects of piscivorous predator removal on coral reef fish community structure. In *Gutshop 81: Fish food habits studies*, ed. G. M. Caillet and C. A. Simenstad, 258-267. Seattle: Washington Sea Grant Publ.

Bohnsack, J. A. 1983. Resiliency of reef fish communities in the Florida Keys following a January 1977 hypothermal fish kill. *Environ. Biol. Fish.* 9:41-53.

Bohnsack, J. A. 1989. Are high densities of fishes at artificial reefs the result of habitat limitation or behavioral preference? *Bull. Mar. Sci.* 44:631-645.

Bohnsack, J. A., and S. P. Bannerot. 1986. *A stationary visual census techniques for quantitatively assessing community structure of coral reef fishes.* NOAA Tech. Rep. Circ. No. 41.

Bohnsack, J. A., A. Brown, Jr., and D. Harper. 1989. *Automated landings assessment for responsive management (ALARM) Gulf of Mexico commercial reef fish landings, June 1989.* U.S. Department of Commerce, NOAA, NMFS Contrib. No. CRD-88/89-16.

Bohnsack, J. A., D. E. Harper, D. B. McClellan, D. L. Sutherland, and M. W. White. 1987. *A resource survey of fishes within Looe Key National Marine Sanctuary.* National Oceanic and Atmospheric Administration, Office of Ocean and Coastal Resource Management, Tech. Rep. No. OCRM SPD.

Brock, R. E., C. Lewis, and R. C. Wass. 1979. Stability and structure of a fish community on a coral patch reef in Hawaii. *Mar. Biol.* 54:281-292.
Brookfield, C. M., and O. Griswold. 1949. *They all called it tropical.* Miami: Data Press.
Brownell, W. N. 1977. Reproduction, laboratory culture, and growth of *Strombus gigas*, *S. costatum*, and *S. pugilis* in Los Roques, Venezuela. *Bull. Mar. Sci.* 27:668-680.
Brownell, W. N., and J. M. Stevely. 1981. The biology, fisheries, and management of the queen conch, *Strombus gigas*. *Mar. Fish. Rev.* 43(7):1-12.
Carter, M. R., L. A. Burns, T. R. Cavinder, K. R. Duggen, P. C. Fore, D. B. Hicks, H. L. Revelles, and T. W. Schmidt. 1973. *Ecosystem analysis of the Big Cypress Swamp and estuaries.* Atlanta: U.S. Environmental Protection Agency.
Colin, P. L. 1974. Observation and collection of deep-reef fishes off the coasts of Jamaica and British Honduras (Belize). *Mar. Biol.* 24:29-38.
Colin, P. L. 1976. Observations of deep-reef fishes in the Tongue-of-the-Ocean, Bahamas. *Bull. Mar. Sci.* 4:603-605.
Collette, B. B., and F. H. Talbot. 1972. Activity patterns of coral reef fishes with emphasis on nocturnal-diurnal changeover. *Nat. Hist. Mus. Los Angeles County Bull.* 14:98-124.
Colton, D. E. 1978. A description of the fish assemblage associated with a calcium carbonate reef off the Florida Keys. M.S. thesis, Florida Inst. of Technology, Melbourne, FL.
Contillo, J. P. 1989. Recreational billfish survey, western North Atlantic. In *Angler participation in SEFC oceanic pelagic programs 1987*, 23-33. NOAA Tech. Memo. No. NMFS-SEFC-209.
Croker, R. A. 1962. Growth and food of the gray snapper, *Lutjanus griseus*, in Everglades National Park. *Trans. Am. Fish. Soc.* 91(4):379-383.
Darcy, G. H., and E. J. Gutherz. 1984. Abundance and density of demersal fishes on the West Florida shelf, January 1978. *Bull. Mar. Sci.* 34:81-105.
D'Asaro, C. N. 1965. Organogenesis, development, and metamorphosis in the queen conch, *Strombus gigas*, with notes on breeding habits. *Bull. Mar. Sci.* 15:359-416.
Davis, J. C. 1976. Biology of the hogfish *Lachnolaimus maximus* in the Florida Keys. M.S. thesis, Univ. of Miami.
Davis, W. P. 1967. Ecological interactions, comparative biology and evolutionary trends of thirteen pomadasyid fishes at Alligator Reef, Florida Keys. Ph.D. diss., Univ. of Miami.
Devaney, T. 1969. Ecological interpretation of distribution of the lanternfishes (Myctophidae) in the Straits of Florida. Ph.D. diss., Univ. of Miami.
Doherty, P. J. 1983. Tropical territorial damselfishes: Is density limited by aggression or recruitment? *Ecology* 64:176-190.
Dooley, J. K. 1972. Fishes associated with the pelagic *Sargassum* complex, with a discussion of the *Sargassum* community. *Contrib. Mar. Sci.* 16:1-32.
Ehrhardt, N. M., D. J. Die, and V. R. Restrepo. In press. Abundance and impact of fishing on a stone crab (*Menippe mercenaria*) population in Everglades National Park, Florida. *Bull. Mar. Sci.*
Emery, A. R. 1968. Comparative ecology of damselfishes (Pisces: Pomacentridae) at Alligator Reef, Florida Keys. Ph.D. diss., Univ. of Miami.
Endicott, W. 1925. *Adventures with rod and harpoon along the Florida Keys.* New York: Frederick A. Stokes.
Essig, R. J., M. C. Holliday, and J. R. Zweifel. 1988. *Comparison and evaluation (methodologies and results) of the Marine Recreational Fishery Statistics Survey and logbooks for charterboat data in the southeastern United States.* U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. Miami.
Florida Marine Fisheries Commission. 1989. *Marine Fisheries Commission approved rules.* Tallahassee.
Fore, P. L., and T. W. Schmidt. 1973. Ecology and early life history of juvenile snook, *Centropomus undecimalis* in the Ten Thousand Islands, Florida. In *103rd Annual Conference, American Fisheries Society* (MS).
Funicelli, N. A., D. A. Meineke, H. E. Bryant, M. R. Dewey, G. M. Ludwig, and L. S. Mengel. 1989. Movements of the striped mullet, *Mugil cephalus*, tagged in Everglades National Park, Florida. *Bull. Mar. Sci.* 44(1):171-178.
Gilbert, C. 1972. Characteristics of the western Atlantic reef fish fauna. *Q. J. Fla. Acad. Sci.* 35:130-144.
Goldman, B., and F. H. Talbot. 1976. Aspects of the ecology of coral reef fishes. *In Biology and geology of coral reefs, Vol. III (Biology 2)*, ed. P. A. Jones and K. Endean. New York: Academic Press.
Goodyear, C. P. 1989. *Status of the red drum stocks of the Gulf of Mexico report for 1989.* U.S. Department of Commerce, NOAA, NMFS Contrib. No. 88/89-14.
Goreau, T. F. 1959. The ecology of Jamaican coral reefs. *Ecology* 40:67-90.
Greene, L. E., and W. S. Alevizon. 1989. Comparative accuracies of visual assessment methods for coral reef fishes. *Bull. Mar. Sci.* 44:899-912.
Greenfield, D. W., and T. A. Greenfield. 1982. Habitat and resources partitioning between two species of *Acanthemblemaria* (Pisces: Chaonopsidae), with comments on the chaos hypothesis. In *The Atlantic barrier ecosystem at Carrie Bow Cay, Belize. I: Structure and communities*, ed. K. Rutzler and I. G. MacIntyre. Washington, DC: Smithsonian Press.
Gulf of Mexico and South Atlantic Fishery Management Councils. 1982. *Fishery management plan, environmental impact statement, and regulatory impact review for spiny lobster in the Gulf of Mexico and South Atlantic.* Tampa and Charleston.
Gulf of Mexico and South Atlantic Fishery Management Councils. 1985. *Amendment 1 to the fishery management plan, environmental impact statement for the coastal migratory pelagic resources (mackerels).* Tampa and Charleston.
Gulf of Mexico and South Atlantic Fishery Management Councils. 1989. *Amendment 2 to the fishery management plan for spiny lobster in the Gulf of Mexico and South Atlantic including environmental assessment and regulatory impact review.* Tampa and Charleston.
Gulf of Mexico Fishery Management Council. 1979. *Fishery management plan for the stone crab fishery of the Gulf of Mexico.* Tampa.
Gulf of Mexico Fishery Management Council. 1981. *Fishery management plan for the shrimp fishery of the Gulf of Mexico, United States waters.* Tampa.

Gulf of Mexico Fishery Management Council. 1987. *Amendment number 1 and environmental assessment and supplemental regulatory impact review, regulatory flexibility analysis for the red drum fishery of the Gulf of Mexico*. Tampa.
Gunter, G., and G. Hall. 1965. A biological investigation of the Caloosahatchee Estuary of Florida. *Gulf Res. Rep.* 2(1):1-72.
Harmic, J. L., C. M. Courtney, T. Edmond, J. C. Kinch, W. O. Key, B. J. Appleby, J. M. Hatcher, and W. L. O'Harra. 1974. Annual report, Marco Applied Marine Ecology Station.
Helfman, G. S., J. L. Meyer, and W. N. McFarland. 1982. The ontogeny of twilight migration patterns in grunts (Pisces: Haemulidae). *Anim. Behav.* 30:317-326.
Henshall, J. A. 1891. Report upon a collection of fishes made in southern Florida during 1889. *Bull. U.S. Fish. Commer.* 9:371-389.
Herrnkind, W. F., and M. J. Butler. 1986. Factors regulating postlarval settlement and juvenile microhabitat use by spiny lobsters, *Panulirus argus*. *Mar. Ecol. Prog. Ser.* 34:23-30.
Herrnkind, W. F., M. J. Butler, and R. A. Tankersley. 1988. The effects of siltation on recruitment of spiny lobster, *Panulirus argus*. *Fish. Bull.* 86(2):331-338.
Herrnkind, W. F., J. Vanderwalker, and L. Barr. 1975. Population dynamics, ecology, and behavior of spiny lobster, *Panulirus argus*, of St. John, U.S. Virgin Islands: Habitation and pattern of movements. Results of the Tektite Program, Vol. 2. *Nat. Hist. Mus. Los Angeles County Bull.* 20:31-45.
Hobson, E. S. 1973. Diel feeding migrations in tropical reef fishes. *Helgol. wiss. Meeresunters.* 24:361-370.
Hobson, E. S. 1974. Feeding relationships of teleostean fishes on coral reefs in Kona, Hawaii. *Fish. Bull.* 72:915-1031.
Hobson, E. S., and J. R. Chess. 1976. Trophic interactions among fishes and zooplankton near shore at Santa Catalina Island, California. *Fish. Bull.* 74:657-698.
Hobson, E. S., and J. R. Chess. 1978. Trophic relationships among fishes and plankton in the lagoon at Eniwetak Atoll, Marshall Islands. *Fish. Bull.* 76:133-153.
Hudson, H. J., T. J. Costello, and D. Allen. 1970. *The flora and fauna of a basin in central Florida Bay*. U.S. Fish and Wildlife Service, Bureau of Commercial Fisheries, Spec. Sci. Rep. Fish No. 604.
Huntsman, G. R. 1976. Offshore headboat fishing in North Carolina and South Carolina. *Mar. Fish. Rev.* 38(3):13-23.
Huntsman, G. R., and J. R. Waters. 1987. Development of management plans for reef fishes--Gulf of Mexico and U.S. South Atlantic. In *Tropical Snappers and Groupers: Biology and Fisheries Management*, ed. J. J. Polovina and S. Ralston, 533-560. Boulder: Westview Press.
Iversen, E. S., D. E. Jory, and S. P. Bannerot. 1986. Predation on queen conchs, *Strombus gigas*, in the Bahamas. *Bull. Mar. Sci.* 39:61-75.
Iversen, E. S., E. S. Rutherford, S. P. Bannerot, and D. E. Jory. 1987. Biological data on Berry Islands (Bahamas) queen conchs, *Strombus gigas*, with mariculture and fishery management implications. *Fish. Bull.* 85(2):299-310.
Jones, R. S., and M. J. Thompson. 1978. Comparison of Florida reef fish assemblages using a rapid visual technique. *Bull. Mar. Sci.* 28:159-172.
Juhl, R. 1966. Experimental fish trawling survey along the Florida west coast. *Commer. Fish. Rev.* 28:1-5.
Klima, E. F. 1976. Snapper and grouper resources of the western central Atlantic Ocean. In *Proceedings, colloquium on snapper-grouper fishery resources of the western central Atlantic Ocean*, ed. H. R. Bullis and A. C. Jones, Jr., 5-18. Florida Sea Grant Program Rep. No. 17.
Klima, E. F., G. A. Matthews, and F. J. Patella. 1986. Synopsis of the Tortugas pink shrimp fishery, 1960-1983, and the impact of the Tortugas Sanctuary. *N. Am. J. Fish. Mgmt.* 6:301-310.
Kutkuhn, J. H. 1962. Gulf of Mexico commercial shrimp populations--trends and characteristics, 1956-1959. *U.S. Fish Wild. Serv. Fish. Bull.* 62:343-402.
Lagler, K. F., J. E. Bandach, R. R. Miller, and D. M. Passino. 1977. *Ichthyology*, 2nd ed. New York: John Wiley and Sons.
Lee, T. N. 1988. Physical oceanography literature review of the Straits of Florida and eastern Gulf of Mexico. Unpubl. manuscript.
Lindall, W. N., J. R. Hall, W. A. Fable, Jr., and L. A. Collins. 1973. Fishes and commercial invertebrates of the nearshore and estuarine zone between Cape Romano and Cape Sable, Florida. In *South Florida ecological study, Appendix E. Estuarine dependent marine fishes*. National Marine Fisheries Service.
Lindberg, W. J., and M. J. Marshall. 1984. *Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (South Florida). Stone crab*. FWS/OBS-82/11.21. U.S. Fish and Wildlife Service, Division of Biological Services.
Lobel, P. S. 1989. Ocean current variability and the spawning season of Hawaiian reef fishes. *Environ. Biol. Fish.* 24:161-171.
Lobel, P. S., and J. C. Ogden. 1981. Foraging by the herbivorous parrotfish *Sparisoma radians*. *Mar. Biol.* 64:173-183.
Longley, W. H., and S. F. Hildebrand. 1941. *Systematic catalogue of the fishes of Tortugas, Florida, with observations on color, habits, and local distribution*. Pap. Tortugas Lab. 34, Carnegie Inst. Wash. Publ. No. 535.
Lonnberg, A. J. E. 1894. List of fishes observed and collected in South Florida. *Ofvers. Kougl. Akad. Forh.* 3:109-131.
Lyons, W. G. 1980. Possible sources of Florida's spiny lobster population. *Proc. Gulf Caribb. Fish. Inst.* 33:253-266.
Lyons, W. G. 1986. Problems and perspectives regarding recruitment of spiny lobsters, *Panulirus argus*, to the South Florida fishery. *Can. J. Fish. Aq. Sci.* 43:2099-2106.
Lyons, W. G., D. G. Barber, S. M. Foster, F. S. Kennedy, Jr., and G. R. Milano. 1981. *The spiny lobster, Panulirus argus, in the Middle and Upper Florida Keys: Population structure, seasonal dynamics, and reproduction*. Fla. Mar. Res. Publ. No. 38. St. Petersburg: Florida Department of Natural Resources, Marine Research Laboratory.
Marshall, N. B. 1966. *The life of fishes*. Cleveland: World Publishing Co.
Marx, J. M., and W. F. Herrnkind. 1986. Macroalgae (Rhodophyta: *Laurencia* spp.) as habitat for young juvenile spiny lobsters, *Panulirus argus*. *Bull. Mar. Sci.* 36:423-431.

McFarland, W. N., J. C. Ogden, and J. N. Lythgoe. 1979. The influence of light on the twilight migrations of grunts. *Environ. Biol. Fish.* 4:9-22.
McGowan, M. F., and W. J. Richards. 1986. Distribution and abundance of bluefin tuna (*Thunnus thynnus*) larvae in the Gulf of Mexico in 1982 and 1983 with estimates of the biomass and population size of the spawning stock for 1977, 1978, and 1981-83. *Collect. Vol. Sci. Pap. ICCAT* 24:182-195.
Menzies, R. A., and J. M. Kerrigan. 1980. The larval recruitment problem of the spiny lobster. *Fisheries* 5(4):43-46.
Milliman, J. D. 1973. Caribbean coral reefs. In *Biology and geology of coral reefs, Vol. I (Geology 1)*, ed. P. A. Jones and K. Endean, 125-151. New York: Academic Press.
Moffitt, R. B., F. A. Parrish, and J. J. Polovina. 1989. Community structure, biomass, and productivity of deepwater artificial reefs in Hawaii. *Bull. Mar. Sci.* 44:616-630.
Molles, M. C. 1978. Fish species on model and natural reef patches: experimental insular biogeography. *Ecol. Monogr.* 48:289-306.
Moyle, P. B., and J. J. Cech, Jr. 1988. *Fishes*, 2nd edition. Englewood Cliffs: Prentice-Hall.
Munroe, R. M., and V. Gilpin. 1930. *The commodore's story*. Miami: Historical Association of Southern Florida.
Nichols, S. 1986. Updated yield-per-recruit information on the Tortugas pink shrimp fishery. *N. Am. J. Fish. Mgmt.* 6:339-343.
Odum, W. E., C. C. McIvor, and T. J. Smith III. 1982. *The ecology of the mangroves of South Florida: A community profile*. FWS/OBS-81/24. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.
Ogden, J. C., and J. P. Ebersole. 1981. Scale and community structure of coral reef fishes: A long-term study of a large artificial reef. *Mar. Ecol. Prog. Ser.* 4:97-104.
Ogden, J. C., and J. C. Zieman. 1977. Ecological aspects of coral reef-seagrass bed contacts in the Caribbean. In *Proceedings, Third International Symposium on Coral Reefs, Vol. 3*, 377-382. Miami, FL.
Phares, P. L. 1985. *Analysis of stone crab assessment data for 1979 to 1985 and evaluation of the logbook data collection system*. U.S. Department of Commerce, NOAA, NMFS Contrib. No. ML1-85-27.
Pollard, D. A. 1984. A review of ecological studies on seagrass-fish communities, with particular reference to recent studies in Australia. *Aquat. Bot.* 18:3-42.
Powers, J. E., and P. Eldridge. 1983a. *A preliminary assessment of king mackerel resources of the southeast United States*. Miami: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service.
Powers, J. E., and P. Eldridge. 1983b. *Assessment of Gulf of Mexico and South Atlantic king mackerel*. Miami: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service.
Randall, J. E. 1963. An analysis of the fish populations of artificial and natural reefs in the Virgin Islands. *Caribb. J. Sci.* 3:31-47.
Randall, J. E. 1964. Contributions to the biology of the queen conch *Strombus gigas*. *Bull. Mar. Sci. Gulf Carib.* 14:246-295.
Randall, J. E. 1967. Food habits of reef fishes of the West Indies. *Stud. Trop. Oceanogr.* 5:665-847.
Rathbun, R. 1887. The crab, lobster crayfish, rock lobster, shrimp, and prawn fisheries. In *The fisheries and fishery industries of the United States*, ed. G. Browne Goode, 650-669. Section 5, 2(21).
Restrepo, V. R. 1989. The dynamics of the stone crab, *Menippe mercenaria*, in the Southwest Florida fishery: Yield-per-recruit assessment through computer simulation. Ph.D. diss., Univ. of Miami.
Richards, W. J., T. Potthoff, and E. D. Houde. 1981. Abundance of bluefin tuna larvae and estimates of spawning stock sizes in the Gulf of Mexico in 1977 and 1978. *Collect. Vol. Sci. Pap. ICCAT* 15(2):273-277.
Richardson, R. 1986. *A descriptive survey of a hardground habitat in the Florida Keys*. Unpubl. biological research report. Dept. of Biological Sciences, Florida Inst. of Technology, Melbourne, FL.
Robblee, M. B., and J. C. Zieman. 1984. Diel variation in fish fauna of a tropical seagrass feeding ground. *Bull. Mar. Sci.* 34:335-345.
Robins, C. R. 1971. Distributional patterns of fishes from coastal and shallow waters of the tropical western Atlantic. *FAO Fish. Rep.* (71.2):249-255.
Rockland, D. B. 1988. *The economic impact of the sport and commercial fisheries of the Florida Keys*. Report prepared for Everglades Protection Association, Florida Conservation Association, and Monroe County Industrial Development Authority. Washington, DC: Sport Fishing Institute.
Rosseler, M. A. 1970. A checklist of the fishes in Buttonwood Canal, Everglades National Park, Florida and observations on the seasonal occurrence and life histories of selected species. *Bull. Mar. Sci.* 20:860-893.
Russel, B. C., F. H. Talbot, and S. Domm. 1974. Patterns of colonization of artificial reefs by coral reef fishes. In *Proceedings of the Second International Symposium on Coral Reefs*, Vol. I, 217-225. Brisbane, Australia.
Russell, R. 1989. Tuna management. *Sport Fishing* 4(6):40-44.
Rutherford, E. S., J. T. Tilmant, E. B. Thue, and T. W. Schmidt. 1989a. Fishery harvest and population dynamics of spotted seatrout, *Cynoscion nebulosus*, in Florida Bay and adjacent waters. *Bull. Mar. Sci.* 44(1):108-125.
Rutherford, E. S., J. T. Tilmant, E. B. Thue, and T. W. Schmidt. 1989b. Fishery harvest and population dynamics of gray snapper, *Lutjanus griseus*, in Florida Bay and adjacent waters. *Bull. Mar. Sci.* 44(1):139-154.
Sale, P. F. 1977. Maintenance of high diversity in coral reef fish communities. *Am. Nat.* 1977:337-359.
Sale, P. F. 1980. The ecology of fishes on coral reefs. *Oceanogr. Mar. Biol. Annu. Rev.* 18:367-421.
Sale, P. F., and Douglas. 1984. Temporal variability in the community structure of fish on coral patch reefs and the relation of community structure to reef structure. *Ecology* 65:409-422.
Sale, P. F., and R. Dybdahl. 1975. Determinants of community structure for coral reef fishes in an experimental habitat. *Ecology* 56:1343-1355.
Schmidt, T. W. 1979. *Ecological study of fishes and the water quality characteristics of Florida Bay, Everglades National Park, FL*. Everglades National Park, Final Project Rep.34 No. RSP-EVER-N-36.
Schroeder, W. C. 1924. *Fisheries of Key West and the clam industry of southern Florida*. Rep. U.S. Commer. Fish. for 1923, App. 12, 1-74, U.S. Bur. Fish. Doc. No. 962.
Scott, E. L., and J. Tashiro. 1989. Cooperative game fish tagging program. In *Angler participation in SEFC oceanic pelagic programs*, 34-48, NOAA Tech. Memo. NMFS-SEFC-209.

Scott, G. P., M. R. Dewey, L. J. Hansen, R. E. Owen, and E. S. Rutherford. 1989. How many mullet are there in Florida Bay? *Bull. Mar. Sci.* 44(1):89-107.
Smith, C. L. 1973. Small rotenone stations: a tool for studying coral reef fish communities. *Am. Mus. Novit.* 2512:1-21.
Smith, C. L., and J. C. Tyler. 1975. Succession and stability in fish communities of dome-shaped patch reefs in the West Indies. *Am. Mus. Novit.* 2572:1-18.
Sogard, S. M., G. V. N. Powell, and J. G. Holmquist. 1987. Epibenthic fish communities on Florida Bay banks: Relationships with seagrass cores and physical environment. *Mar. Ecol. Prog. Ser.* 40:25-39.
South Atlantic Fishery Management Council. 1983. *Source document for the snapper-grouper fishery of the South Atlantic region.* Charleston.
South Atlantic Fishery Management Council. 1985. *Fishery management plan, regulatory impact review, initial regulatory flexibility analysis, and final environmental impact statement for Atlantic swordfish.* Charleston.
South Atlantic Fishery Management Council. 1988. *Source document for the fishery management plan for the Atlantic billfishes.* Charleston.
Springer, V. C., and A. J. McErlean. 1962. A study of the behavior of some tagged South Florida coral reef fish. *Am. Midl. Nat.* 67:386-397.
Starck, W.A. II. 1968. A list of fishes of Alligator Reef, Florida with comments on the nature of the florida reef fish fauna. *Undersea Biol.* 1:5-40.
Starck, W. A., and W. P. Davis. 1966. Night habits of fishes of Alligator Reef, Florida. *Ichthyology* 38:313-355.
Steiger, J. C. 1970. The distribution of benthic fishes found below two hundred meters in the Straits of Florida. Ph.D. diss., Univ. of Miami.
Stewart, K. W. 1961. Contributions to the biology of the spotted seatrout (*Cynoscion nebulosus*) in the Everglades National Park, FL. M.S. thesis, Univ. of Miami.
Stoner, A. W. 1983. Distribution ecology of amphipods and tanaidaceans associated with three seagrass species. *J. Crust. Biol.* 3:505-518.
Sullivan, J. R. 1979. *The stone crab, Menippe mercenaria, in the Southwest Florida fishery.* Fla. Mar. Res. Publ. No. 36. St. Petersburg: Florida Department of Natural Resources, Marine Research Laboratory.
Tabb, D. C., and R. B. Manning. 1961. A checklist of the flora and fauna of northern Florida Bay and adjacent brackish waters of the Florida mainland collected during the period July 1957 through September 1960. *Bull. Mar. Sci. Gulf Caribb.* 11:552-649.
Tabb, D. C., D. Dubrow, and R. Manning. 1962. The ecology of northern Florida Bay and adjacent estuaries. *Tech. Ser. Fla. State Bd. Conserv.* 39:1-79.
Thayer, G. W., D. R. Colby, and W. F. Hettler. 1987. Utilization of the red mangrove prop root habitat by fishes in South Florida. *Mar. Ecol. Prog. Ser.* 35:25-38.
Tilmant, J. 1989. A history and overview of recent trends in the fisheries of Florida Bay. *Bull. Mar. Sci.* 44(1):3-22.
Tilmant, J. T., E. S. Rutherford, and E. B. Thue. 1989. Fishery harvest and population dynamics of red drum (*Sciaenops ocellatus*) from Florida Bay and adjacent waters. *Bull. Mar. Sci.* 44(1):126-138.
U.S. Department of Commerce. 1986. *Secretarial fishery management plan, regulatory impact review, and regulatory flexibility analysis for the red drum fishery of the Gulf of Mexico.* Washington, DC.
U.S. Department of Commerce. 1989a. *Report of the NMFS swordfish stock assessment workshop March 20-24, 1989.* Miami: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service.
U.S. Department of Commerce. 1989b. *Special edition - swordfish.* NMFS Newsbreaker No. 89-06. St. Petersburg.
U.S. Department of Commerce. 1989c. *Temporary opening of 54-square mile area of Tortugas shrimp sanctuary and annual shrimp closure off Texas.* NMFS Newsbreaker No. 89-05. St. Petersburg.
Victor, B. D. 1983. Recruitment and population dynamics of a coral reef fish. *Science* 219:419-420.
Wang, J. C., and E. C. Raney. 1971. Distribution and fluctuations in the fish fauna of the Charlotte Harbor Estuary, FL. Sarasota: Mote Marine Laboratory.
Weinstein, M. P., and K. L. Heck, Jr. 1979. Ichthyofauna of seagrass meadows along the Caribbean coast of Panama and in the Gulf of Mexico: Composition, structure and community ecology. *Mar. Biol.* 50:97-104.
Wellington, G. M., and B. C. Victor. 1985. El Nino mass coral mortality: A test of resource limitation in a coral reef damselfish population. *Oecologia* 68:15-19.
Williams, D. McB. 1980. Dynamics of the pomacentrid community on small patch reefs in One Tree Lagoon (Great Barrier Reef). *Bull. Mar. Sci.* 30:159-170.
Williams, D. McB., and P. F. Sale. 1981. Spatial and temporal patterns of recruitment of juvenile coral reef fishes to coral habitats within One Tree Lagoon, Great Barrier Reef. *Mar. Biol.* 65:245-253.
Wilson, C. A. 1988. *Longlining for yellowfin tuna in the Gulf of Mexico.* Baton Rouge: Louisiana Sea Grant College, Louisiana State Univ.
Yang, W. T., and G. E. Krantz. 1976. *Intensive culture of the stone crab, Menippe mercenaria.* Florida Sea Grant Tech. Bull. No. 35.
Yokel, B. J. 1966. A contribution to the biology and distribution of the red drum, *Sciaenops ocellatus.* Master's thesis, Univ. of Miami.
Yoshioka, P. M. 1982. Role of planktonic and benthic factors in the population dynamics of the bryozoan *Membranipora membranacea. Ecology* 63:457-468.
Zweifel, J. R. 1988. *Operations manual for the Trip Interview Program in the State/Federal Cooperative Statistics Program (TIP).* Miami: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service.

CHAPTER 8
MARINE MAMMALS AND SEA TURTLES

Daniel K. Odell

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INTRODUCTION

Marine mammals and sea turtles are widely distributed in the marine environment from coastal estuaries to deep ocean waters. Most are carnivorous, but both groups include herbivores. Most species of marine mammals and all species of sea turtles have been exploited by humans for food, oil, bone, ivory, baleen, etc. Many species have seriously declined from historic levels of abundance and are considered Endangered or Threatened. Although most commercial harvesting of marine mammals and sea turtles has ended, illegal harvest continues in some areas. In addition, other human activities are killing these animals in increasing numbers. These include incidental take in fisheries (drift gillnets, purse seines, long-lines, shrimp trawls), destruction of coastal and nearshore habitats (nesting beaches, seagrass beds), competition for food, pollution, etc. The continued existence of many marine mammal and sea turtle populations depends on the rapid resolution of conflicts with human activities. New activities in the marine environment, as well as established activities in new places, must be carefully evaluated to minimize or eliminate effects on these creatures.

MARINE MAMMALS

Background

Marine mammals include the cetaceans, pinnipeds, sirenians, the sea otter, and polar bears. The cetaceans (Order Cetacea) are divided into two suborders: Mysticeti (baleen whales), and Odontoceti (toothed whales). The pinnipeds (Order Pinnipedia) include the seals, sea lions, and walrus. The Order Sirenia includes manatees and dugongs, the only herbivorous marine mammals. The sea otter (Carnivora: Mustellidae) is one of the smallest and most recent (geologically) marine mammals. Polar bears (Carnivora: Ursidae) are also considered marine mammals in a legal sense (Marine Mammal Protection Act).

Marine mammals occupy a variety of positions in the marine ecosystem. They are generally carnivorous (with the exception of the sirenians). They feed on a variety of organisms ranging in size from copepods to other marine mammals. They range from strictly freshwater (some river dolphins and the Amazonian manatee) to estuarine, to coastal, to deep ocean waters, and from the poles to the equator.

Historically, information on marine mammals has come from but a few sources. Directed fisheries have provided vast amounts of data on some species, yet the record is often incomplete because the fisheries exploit the animals at times of the year when they are concentrated (breeding, calving, nesting season). Species not taken commercially are sometimes taken incidentally to other fisheries (e.g., dolphins in tuna purse seines). Scientists have used these specimens for studies on the basic biology of the species involved. Still other species are known only from the examination of animals washed up dead on the beaches. Laboratory and field studies are possible but are limited by logistic considerations and our ability to maintain most species in a captive environment.

Species of marine mammals that are known or suspected to occur in the study area are listed in **Table 8.1.** The Endangered/Threatened status of each species, if applicable, is included in the table. Brief discussions of each species are presented below. For convenience, references pertaining to each species are listed at the end of each subsection.

Table 8.1. Marine mammals known or suspected to occur in the study area.

Species	Common Name	Figure No.*	Status†	
			Federal	State
CETACEA				
Mysticeti				
Balaenidae				
Eubalaena glacialis	right whale	–	E	E
Balaenopteridae				
Balaenoptera musculus	blue whale	–	E	E
Balaenoptera physalus	fin whale	8.1	E	E
Balaenoptera borealis	sei whale	–	E	E
Balaenoptera edeni	Bryde's whale	–	NL	NL
Balaenoptera acutorostrata	minke whale	8.1	NL	NL
Megaptera novaeangliae	humpback whale	–	E	E
Odontoceti				
Physeteridae				
Physeter macrocephalus	sperm whale	8.2	E	E
Kogia breviceps	pygmy sperm whale	8.2	NL	NL
Kogia simus	dwarf sperm whale	8.2	NL	NL
Delphinidae				
Feresa attenuata	pygmy killer whale	8.3	NL	NL
Grampus griseus	Risso's dolphin	8.4	NL	NL
Globicephala macrorhynchus	short-finned pilot whale	8.4	NL	NL
Lagenodelphis hosei	Fraser's dolphin	8.5	NL	NL
Orcinus orca	killer whale	8.3	NL	NL
Peponocephala electra	melon-headed whale	–	NL	NL
Pseudorca crassidens	false killer whale	8.3	NL	NL
Stenella frontalis	spotted dolphin	8.6	NL	NL
Stenella attenuata	spotted dolphin	8.6	NL	NL
Stenella clymene	short-snouted spinner dolphin	8.7	NL	NL
Stenella longirostris	long-snouted spinner dolphin	8.7	NL	NL
Stenella coeruleoalba	striped dolphin	–	NL	NL
Steno bredanensis	rough-toothed dolphin	8.5	NL	NL
Tursiops truncatus	bottlenose dolphin	–	NL	NL
Ziphiidae				
Mesoplodon densirostris	Blainville's beaked whale	–	NL	NL
Mesoplodon bidens	Sowerby's beaked whale	–	NL	NL
Mesoplodon europaeus	Gervais' beaked whale	8.8	NL	NL
Mesoplodon mirus	True's beaked whale	–	NL	NL
Ziphius cavirostris	Cuvier's beaked whale	8.8	NL	NL
SIRENIA				
Trichechidae				
Trichechus manatus latirostris	Florida manatee	8.9	E	E

* Refers to figures in this chapter showing locations of strandings in the study area.
† E = Endangered; NL = not listed.

Species Accounts

Right Whale (*Eubalaena glacialis*)

The **right whale** is the most Endangered cetacean in the western North Atlantic. The population may be only several hundred animals. Individuals may reach a weight of 100 metric tons and a length of 16 to 17 m (a length of 18 m has been reported, but it is not clear how the measurements were made).

In the western North Atlantic, right whales summer in feeding grounds off New England and eastern Canada. In fall and winter, they migrate southward to ill-defined calving grounds off Georgia and Northeast Florida. Right whales are often seen just outside the surf line along the east coast of Florida in winter. The southernmost sighting in recent years was a female with calf just outside Biscayne Bay. There has been only one stranding and one sighting in the Gulf of Mexico.

In the western North Atlantic, right whales feed exclusively on zooplankton (primarily copepods and euphausiids). Life history parameters (longevity, age at sexual maturity, calving interval) are unknown. Calving intervals for southern right whales range from two to four years.

Occurrence in the Study Area. Although no right whales have been stranded or sighted in the study area, the recent sightings in Dade County and the historic records from the Gulf of Mexico lead to the possibility that right whales may pass through the study area. The study area is not a known feeding, breeding, or calving area.

References. Prescott et al. (1979); Schmidly (1981); Reeves and Brownell (1982); Leatherwood and Reeves (1983); Cummings (1985); Anon. (1986); Brownell et al. (1986); National Marine Fisheries Service (NMFS) (1988); Odell (in press).

Blue Whale (*Balaenoptera musculus*)

The **blue whale**, an Endangered species, is the largest of the baleen whales and the largest animal in the world. The greatest reported length is 33.58 m and the greatest weight, 190 metric tons. Average length is 24 to 26 m.

Blue whales are found in all oceans, but tend to prefer cooler waters. Seasonal migrations are toward the poles in summer for feeding and antipolar in winter. Calving occurs in the warmer waters during winter in the respective hemispheres. In the western North Atlantic, blue whales summer from the Gulf of St. Lawrence and southern Greenland north to the ice edge. The winter range is unknown, but it is assumed to extend from mid-temperate latitudes to the tropics. Aside from the probable stranding (and sighting) records from the Gulf of Mexico, there are no sightings of blue whales south of New Jersey.

Blue whales feed almost exclusively on euphausiids. They become sexually mature at about 10 years of age. Gestation lasts about a year, and the calving interval is two to three years.

Occurrence in the Study Area. There are no blue whale records from the study area. However, the fact that one blue whale (or possibly two) has stranded on the Texas coast leads to the possibility that they may pass through the study area. The study area is not a known breeding, calving, or feeding area.

References. Schmidly (1981); Reeves and Brownell (1982); Leatherwood and Reeves (1983); Yochem and Leatherwood (1985).

Fin Whale (*Balaenoptera physalus*)

The **fin whale**, an Endangered species, is a large baleen whale reaching a length of 22 to 24 m in the Northern Hemisphere and a weight of 80 metric tons.

Fin whales are distributed worldwide, summering in polar/temperate waters and wintering from the ice edge into temperate and tropical waters. In the western North Atlantic, they winter from the ice edge south to Florida, the Greater Antilles to the Gulf of Mexico in offshore waters; they summer from New England to the Arctic.

Fin whales feed on pelagic crustaceans, cephalopods, capelin, herring, cod, mackerel, pollack, sardines, and other schooling fish. Female fin whales appear to have a three-year calving cycle. In the western North Atlantic, fin whales mature at 17 to 18 m length.

Occurrence in the Study Area. Several fin whale strandings have been recorded from the study area (**Figure 8.1**), and the animals can be expected to pass through the Straits of Florida. Frequency of occurrence is unknown. The study area is not a known breeding, feeding, or calving area.

References. Schmidly (1981); Reeves and Brownell (1982); Leatherwood and Reeves (1983); Gambell (1985).

Sei Whale (*Balaenoptera borealis*)

The **sei whale**, an Endangered species, is distributed in all oceans but appears to favor temperate oceanic waters. For some time, the identity of the sei whale and Bryde's whale (*Balaenoptera edeni*) were confused. Leatherwood and Reeves (1983) concluded that many sei whale sightings and strandings in the Gulf of Mexico were Bryde's whales. Recent stranding records support this conclusion, but there have been valid sei whale strandings in the Gulf of Mexico. Most of the information on sei whales comes from exploited populations. However, Mead (1977) concluded that there may be a resident population in the Caribbean and Gulf of Mexico.

Sei whales feed on a variety of copepods, euphausiids, schooling fish, and cephalopods. They reach a length of 17 to 19 m and become sexually mature at 6 to 12 years of age (12 to 13 m for males; 13 to 14 m for females). The calving interval is two to three years. Newborns are 4.5 to 4.8 m long and 8 to 9 m at weaning.

Occurrence in the Study Area. There are no records of sei whales in the study area. Because there are valid records for the Gulf of Mexico, Caribbean, and east coast of Florida, these whales may be expected to occur in the study area from time to time.

References. International Whaling Commission (1977); Schmidly (1981); Reeves and Brownell (1982); Leatherwood and Reeves (1983); Gambell (1985).

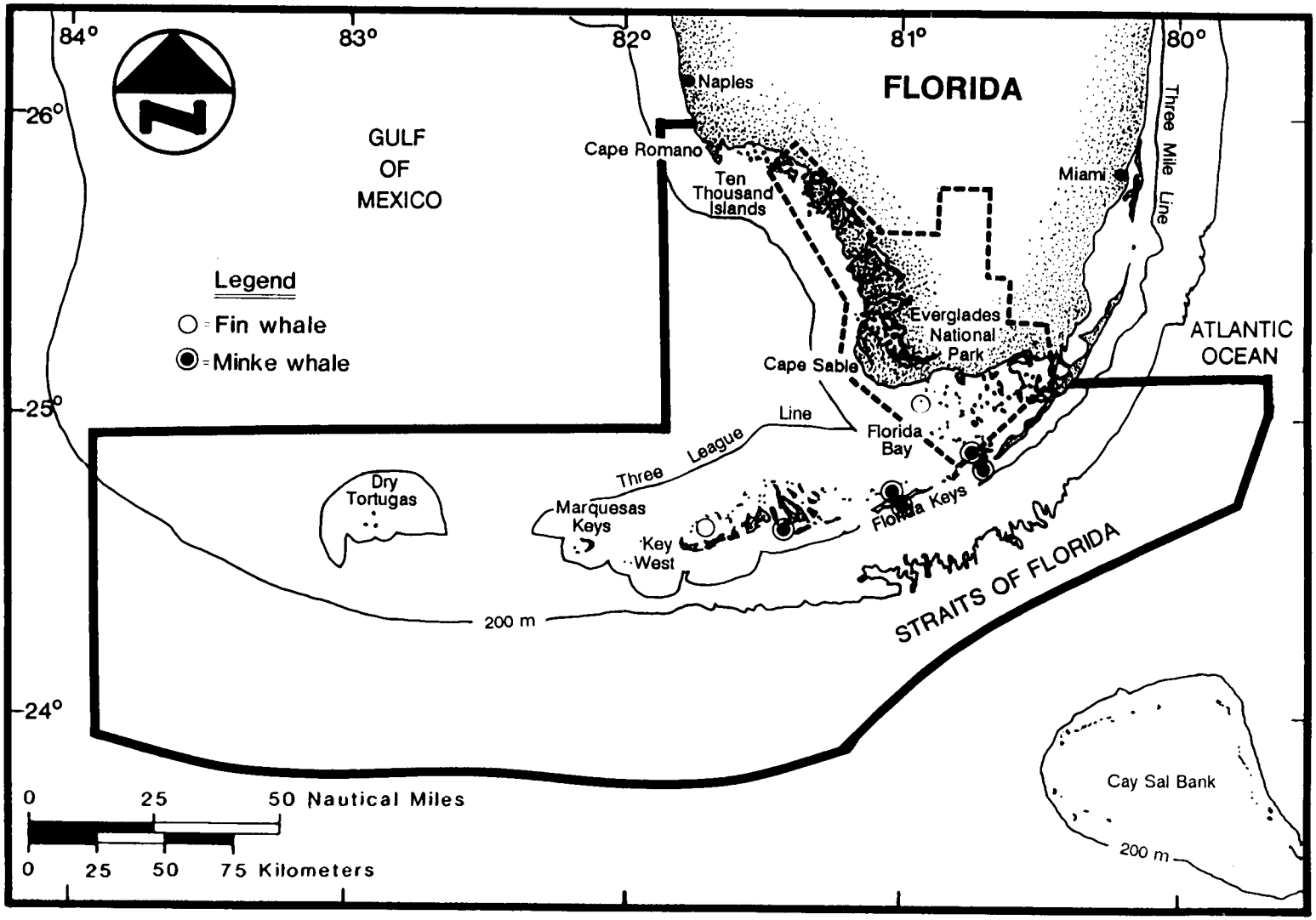

Figure 8.1. Approximate stranding locations in the study area for the fin whale (*Balaenoptera physalus*) and the Minke whale (*Balaenoptera acutorostrata*).

Bryde's Whale (*Balaenoptera edeni*)

The **Bryde's whale** is distributed worldwide in tropical and warm-temperate waters. Identification of the sei and Bryde's whales has been confused, but Bryde's whales are smaller and have three characteristic ridges from blowhole to rostrum.

Bryde's whales feed on a variety of schooling fish, cephalopods, and large pelagic crustaceans. Bryde's whales reach a length of 15.5 m, with an average length of 13 m. Females are slightly larger than males. Sexual maturity is at 12 m in length (10 years for females, 9 to 13 years for males). Gestation lasts about one year, and the calving interval about two years. Calves are about 3.4 m at birth.

Occurrence in the Study Area. There probably is a resident population of Bryde's whales in the Gulf of Mexico. Evidence for a Gulf of Mexico population is based on stranding records (time of year, presence of calves) extending along the east coast of Florida into the Carolinas. However, there are no records of Bryde's whales from the study area. Given their distribution, they are likely to pass through the Straits of Florida.

References. International Whaling Commission (1977); Schmidly (1981); Reeves and Brownell (1982); Leatherwood and Reeves (1983); Cummings (1985).

Minke Whale (*Balaenoptera acutorostrata*)

The **minke whale** is the smallest balaenopterid, reaching a maximum length of about 10 m. The species is found in all oceans. Animals in the Northern Hemisphere are slightly smaller than those in the Southern Hemisphere and have a distinct white band across the flippers. There are no population estimates for minke whales in the Gulf of Mexico.

Minke whales feed on small schooling fish, euphausiids, and copepods in the Northern Hemisphere, and primarily on euphausiids in the Southern Hemisphere. Calves are about 2.5 m long at birth and reach sexual maturity at seven to eight years of age. Unlike the other baleen whales, minke whales have an annual calving cycle. Calves are weaned at about six months of age.

Occurrence in the Study Area. Minke whales have stranded in the study area and the western Gulf of Mexico (**Figure 8.1**). It is likely that they pass through the study area from time to time.

References. Schmidly (1981); Reeves and Brownell (1982); Fritts et al. (1983); Leatherwood and Reeves (1983); Stewart and Leatherwood (1985); Odell (in press).

Humpback Whale (*Megaptera novaengliae*)

The **humpback whale**, an Endangered species, is the most morphologically distinct of the balaenopterids; its white flippers may be almost one-third of its body length. These whales often give spectacular aerial displays.

Humpback whales, which feed on schooling fish and euphausiids, are distributed in all oceans. Like most other baleen whales, they winter in tropical waters and summer in higher latitudes. Humpbacks reach an adult length of 15 to 16 m, with females longer than males. Gestation lasts about 12 months, and calves are 4.5 to 5 m long at birth. Like right whales, humpbacks are highly migratory and are often seen in shallow, coastal waters. In the western North Atlantic, humpbacks summer in the waters of New England and eastern Canada as far north as Newfoundland. The population estimate for the western North Atlantic is about 5,800 animals. The whales migrate, via

Bermuda, to calving grounds on shallow banks in the Caribbean. Humpbacks are occasionally seen in the Gulf of Mexico.

Occurrence in the Study Area. There are no stranding or sighting records of humpback whales in the study area. Because they have been seen on both coasts of Florida, they can be expected to pass through the study area.

References. Schmidly (1981); Reeves and Brownell (1982); Leatherwood and Reeves (1983); Winn and Reichley (1985); NMFS (1988); Odell (in press).

Sperm Whale (*Physeter macrocephalus*)

The **sperm whale** is an Endangered species and occurs worldwide. Historically, the sperm whale was hunted in the Gulf of Mexico and adjacent waters. Considerably more biological data are available for sperm whales than for other species because they have been and continue to be taken in directed fisheries (none currently in the Gulf of Mexico).

Sperm whales are highly sexually dimorphic. Males reach a length of 18 m and females 12 m. Males may reach an average weight of 43.5 metric tons and females 13.5 metric tons. Sperm whales feed primarily on cephalopods. Although their distribution is oceanic, they tend to concentrate near the continental shelf. Figure 10 in Schmidly (1981) summarizes some captures for the eastern Gulf of Mexico taken from Townsend (1935).

Occurrence in the Study Area. A number of sperm whales were taken in and near the study area (**Figure 8.2**). It is likely that sperm whales in the eastern Gulf of Mexico follow the Loop Current southward and then eastward into the Florida Current through the Straits of Florida. It is likely sperm whales feed in the study area and, given that sperm whale calves have stranded in and near the study area, the study area is probably part of a calving area.

References. Townsend (1935); International Whaling Commission (1980); Schmidly (1981); Leatherwood and Reeves (1982, 1983); Rice (1989); Odell (in press).

Pygmy Sperm Whale (*Kogia breviceps*)

The **pygmy sperm whale** is distributed throughout the temperate and tropical oceans. In Florida, it is the second most common single stranded cetacean, after the bottlenose dolphin.

Pygmy sperm whales have an average adult length of 3 m and weigh 300 to 400 kg. Calves are about 1.2 m at birth. Pygmy sperm whales feed primarily on cephalopods, but may consume fish in some parts of their range. They are apparently solitary and are rarely seen at sea. They seem to occupy deep waters along the edge of the continental shelf. Almost all of the information comes from stranded animals. They strand much more frequently on the east coast of Florida than on the west coast--perhaps because deep waters are closer to shore on the east coast.

Occurrence in the Study Area. Pygmy sperm whales have stranded in the study area (**Figure 8.2**) and probably occur in the Straits of Florida and Gulf Stream with some regularity. They likely feed in the deep waters of the study area.

References. Moore (1953); Layne (1965); Handley (1966); Schmidly (1981); Leatherwood and Reeves (1983); Caldwell and Caldwell (1989); Odell (in press).

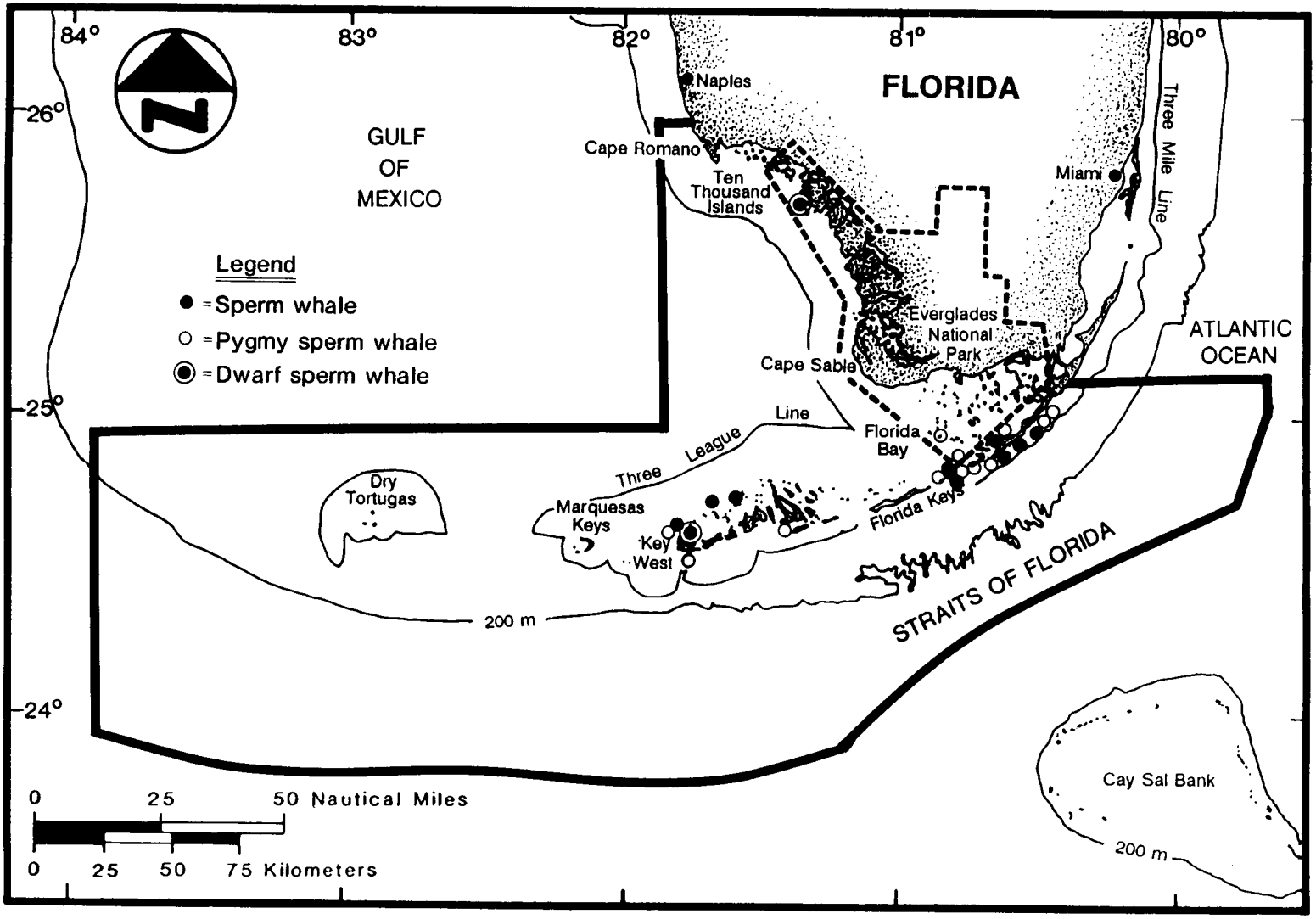

Figure 8.2. Approximate stranding locations in the study area for the sperm whale (*Physeter macrocephalus*), the pygmy sperm whale (*Kogia breviceps*), and the dwarf sperm whale (*Kogia simus*).

Dwarf Sperm Whale (*Kogia simus*)

The **dwarf sperm whale** is the smallest of the three physeterids. This species is easily confused with *Kogia breviceps*, and positive identification usually depends on examination of the teeth. For many years, *K. simus* was recorded as *K. breviceps* until a proper diagnosis was available. Average adult length is 2.1 to 2.7 m, and average weight 136 to 272 kg. Sexual maturity is reached at 2.1 to 2.2 m in both sexes, and there is little sexual dimorphism.

Most biological information on dwarf sperm whales comes from stranded animals; little is known about their distribution at sea. The primary range appears restricted to tropical and subtropical waters. These whales feed mainly on cephalopods. In Florida, dwarf sperm whales probably occur along the edge of the continental shelf where cephalopods occur. Stranding records are from both coasts of Florida, but more frequently from the Atlantic coast.

Occurrence in the Study Area. At least through 1980, there were no confirmed records of dwarf sperm whales in the study area. Since then, there have been two confirmed records for Monroe County (**Figure 8.2**). Although these whales occur and probably feed in the study area, there are no known calving or breeding areas.

References. Handley (1966); Schmidly (1981); Leatherwood and Reeves (1983); Caldwell and Caldwell (1989); Odell (in press).

Pygmy Killer Whale (*Feresa attenuata*)

The **pygmy killer whale** is poorly known, but appears to be distributed in tropical waters. Almost all of the available information comes from stranded animals. Maximum reported length is 2.7 m. Sexual maturity occurs at about 2.2 m in both sexes. These whales probably eat fish and squid, but may attack other small cetaceans. There are no population estimates.

Occurrence in the Study Area. There have been several pygmy killer whale strandings in the study area (**Figure 8.3**). These whales probably occur in deep waters with unknown frequency.

References. Mitchell (1975); White (1976); Forrester et al. (1980); Schmidly (1981); Leatherwood and Reeves (1983); Odell and Asper (1986); Odell (in press).

Risso's Dolphin (*Grampus griseus*)

Risso's dolphin occurs worldwide from tropical to warm temperate seas. Adults reach a length of 3.6 to 4.0 m, with no apparent sexual dimorphism. The species has a diagnostic crease in its melon (forehead), and adults show extensive scarring, presumably from social interactions. Risso's dolphin may occur in herds of up to several hundred individuals. The species is generally found in deep waters and feeds primarily on cephalopods.

Occurrence in the Study Area. Risso's dolphins have stranded in the study area, and there have been recent sightings in the Straits of Florida (**Figure 8.4**).

References. Layne (1965); Caldwell and Caldwell (1973); Mitchell (1975); Schmidly (1981); Fritts et al. (1983); Leatherwood and Reeves (1983); Odell (in press).

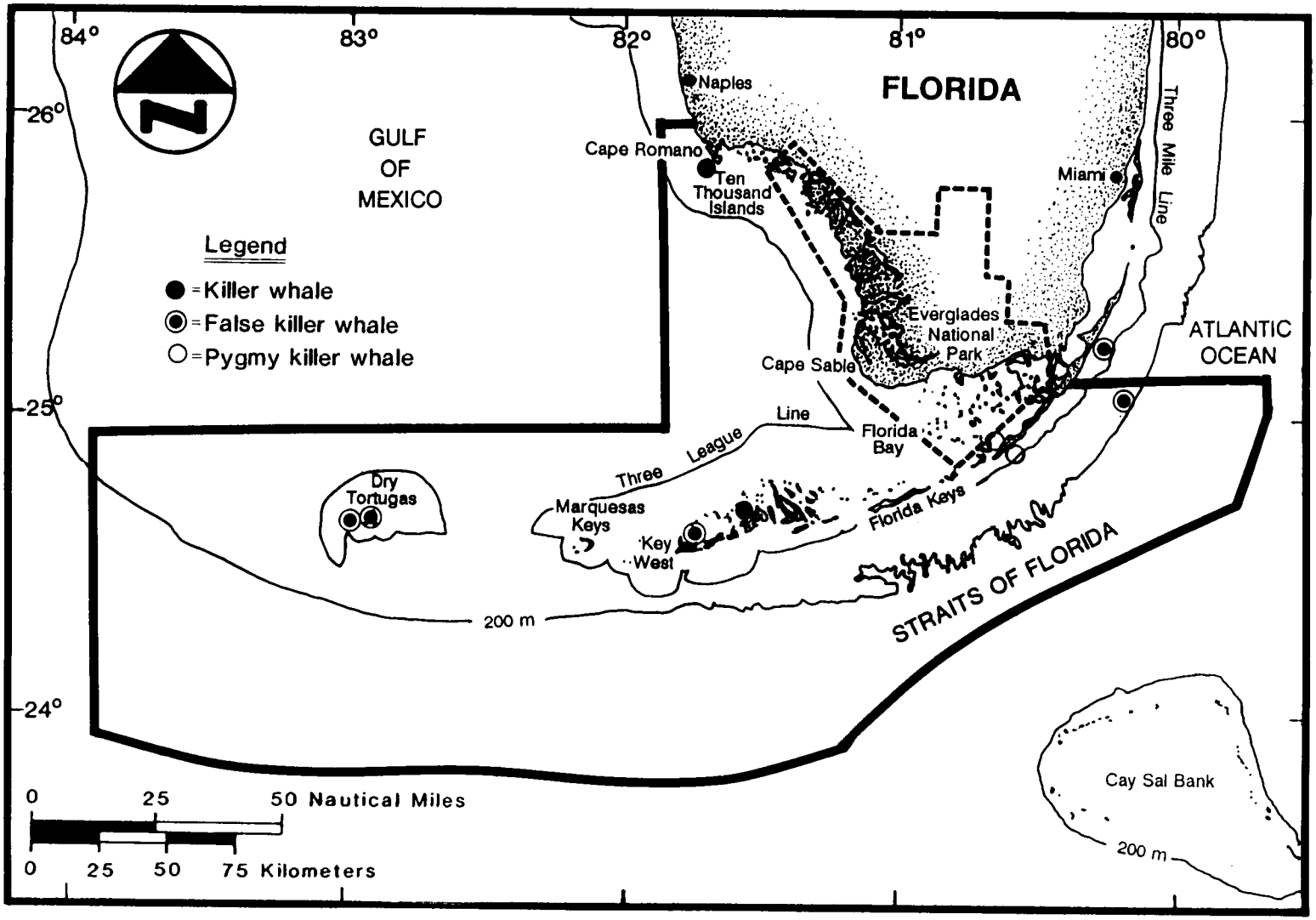

Figure 8.3. Approximate stranding locations in the study area for the killer whale (*Orcinus orca*), the false killer whale (*Pseudorca crassidens*), and the pygmy killer whale (*Feresa attenuata*).

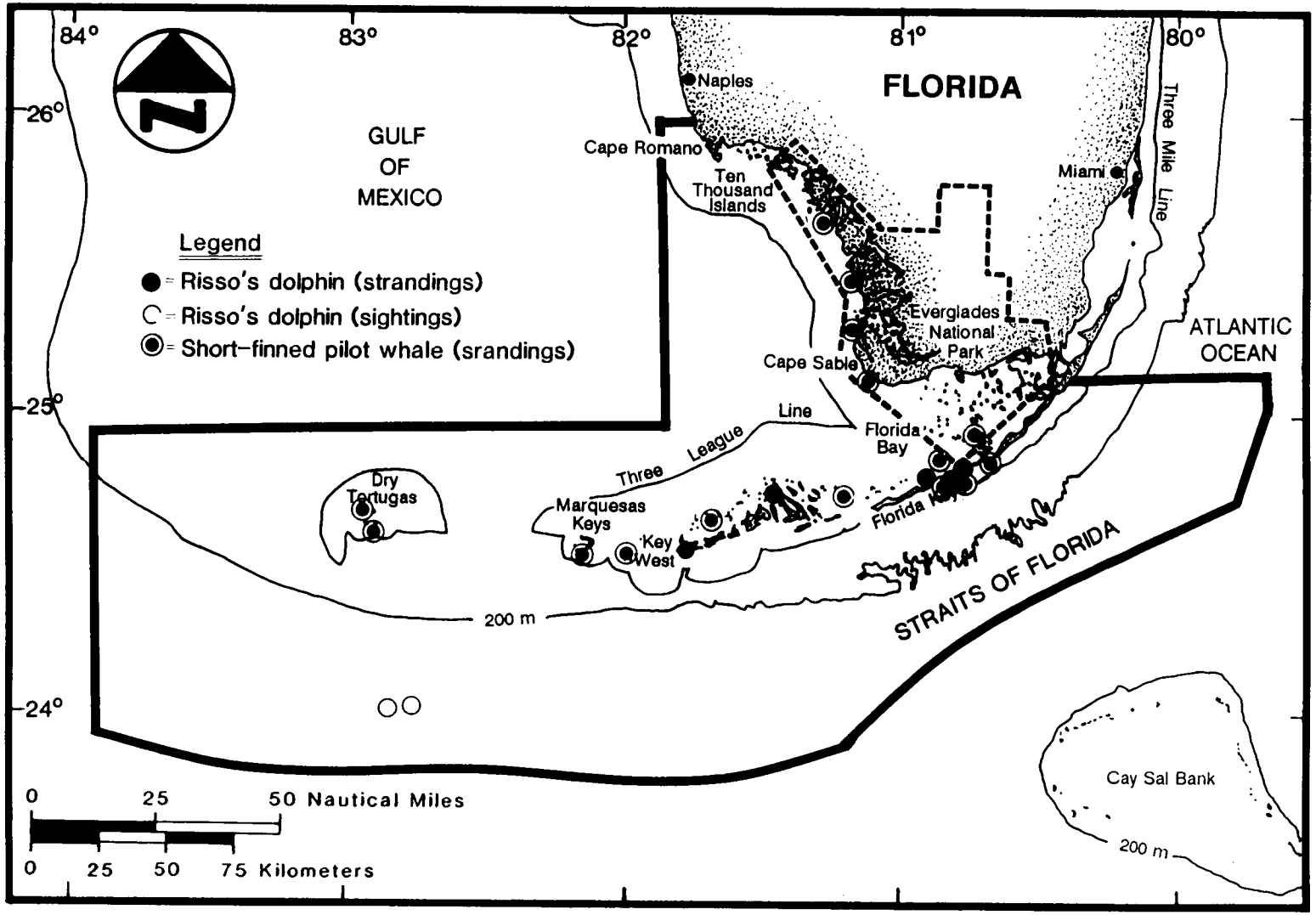

Figure 8.4. Approximate stranding and sighting locations in the study area for Risso's dolphin (*Grampus griseus*) and the short-finned pilot whale (*Globicephala macrorhynchus*).

Short-finned Pilot Whale (*Globicephala macrorhynchus*)

The **short-finned pilot whale** is common from tropical to warm temperate seas worldwide. The species is common in the Gulf of Mexico and along the Atlantic coast of the southeastern U.S. Mass strandings have occurred frequently.

Short-finned pilot whales are sexually dimorphic. Males may reach a length of about 5.4 m and females 4.0 m. Females become sexually mature at about 3.2 m and males at about 4.8 m. Birth length is about 1.4 m. Females may live over 60 years and males over 45 years. The animals feed primarily on cephalopods.

Occurrence in the Study Area. There have been several mass strandings of short-finned pilot whales in the study area and numerous sightings in adjacent waters (**Figure 8.4**). They can be expected to occur in the study area with some regularity.

References. Layne (1965); Caldwell and Caldwell (1973); Mitchell (1975); Schmidly (1981); Reeves and Brownell (1982); Leatherwood and Reeves (1983); Kasuya and Marsh (1984); Odell (in press).

Fraser's Dolphin (*Lagenodelphis hosei*)

Fraser's dolphin is a poorly known small cetacean that is distributed in tropical and subtropical waters of the world. Schmidly (1981) predicted that because of its tropical and subtropical distribution, this species would probably occur in the Gulf of Mexico.

Fraser's dolphins may occur in herds of several hundred or more, and mass strandings have occurred, including one at the Marquesas Keys in 1981. Males and females reach a length of 2.6 m. They seem to feed on mesopelagic fish, cephalopods, and crustaceans.

Occurrence in the Study Area. There is one record of a Fraser's dolphin from the study area (**Figure 8.5**). This is the only record of the species from the Gulf of Mexico. The species may occur in the study area on an infrequent basis.

References. Perrin et al. (1973); Mitchell (1975); Schmidly (1981); Leatherwood and Reeves (1983); Hersh and Odell (1986); van Bree et al. (1986); Odell (in press); Perrin and Leatherwood (in press).

Killer Whale (*Orcinus orca*)

The **killer whale** is distributed in all oceans. Numbers seem to be greater in cooler waters. Standings and several recent live sightings have been reported from the Gulf of Mexico and both coasts of Florida.

Killer whales are sexually dimorphic. Males may reach a length of 9.5 m and have a distinct, tall, dorsal fin. Females reach a length of 7 m. Birth length is 2.1 to 2.4 m. Average longevity is thought to be 25 to 30 years. Males become sexually mature at 5.2 to 6.2 m, females at 4.6 to 5.4 m. Killer whales feed primarily on fish, but may eat other marine mammals, sea turtles, and birds.

Occurrence in the Study Area. There are two old stranding records for killer whales from the study area (**Figure 8.3**). Based on recent sightings in the northern Gulf of Mexico and off Northeast Florida, killer whales may be expected to occur in the study area on an irregular basis.

References. Mitchell (1975); Leatherwood and Reeves (1982, 1983); Heyning and Dalheim (1988); Katona et al. (1988); Mitchell and Reeves (1988); Sigurjonsson and Leatherwood (1988); Odell (in press).

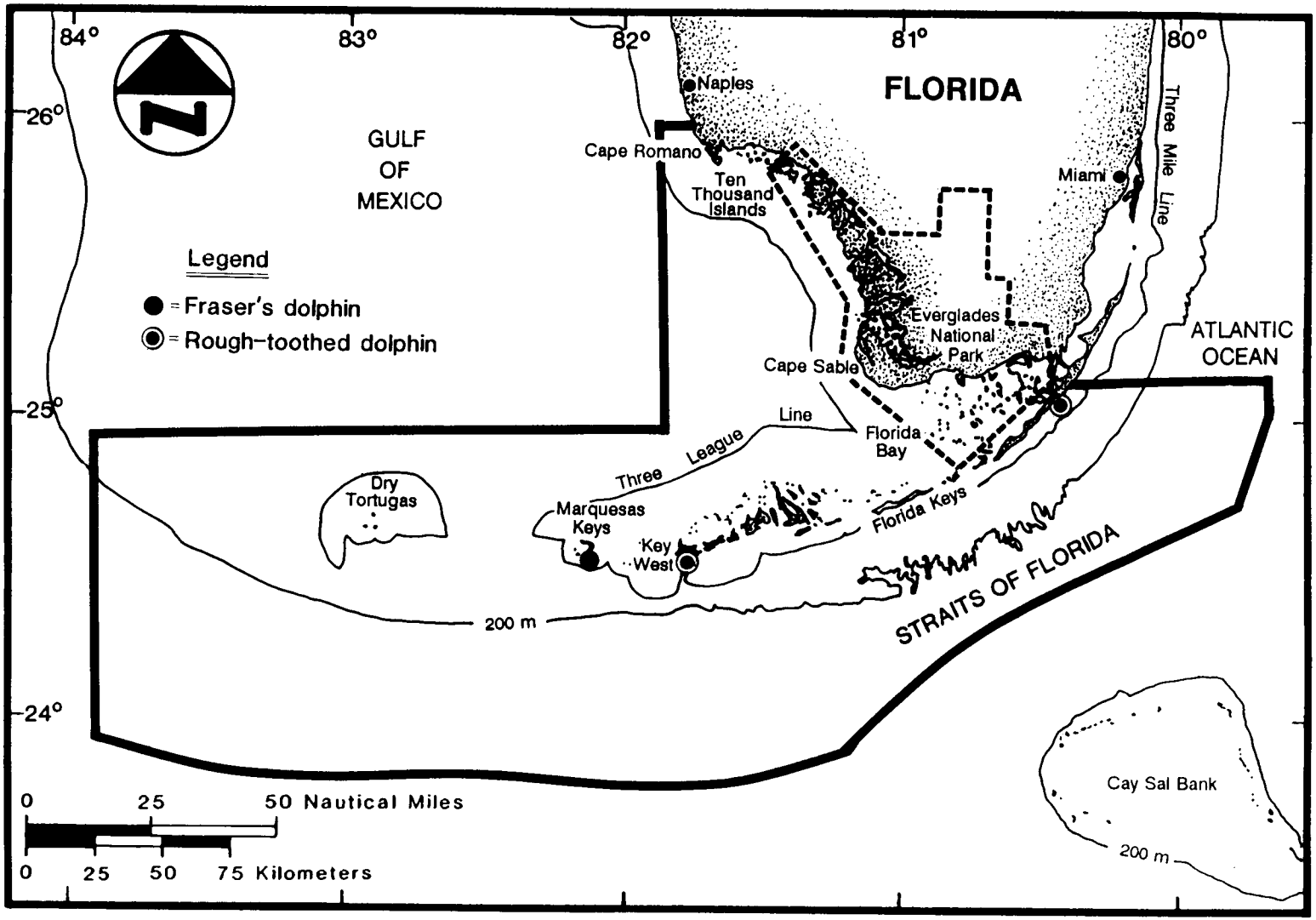

Figure 8.5. Approximate stranding locations in the study area for Fraser's dolphin (*Lagenodelphis hosei*) and the rough-toothed dolphin (*Steno bredanensis*).

Melon-headed Whale (*Peponocephala electra*)

The **melon-headed whale** is similar in appearance and size to the pygmy killer whale. The species appears to be distributed worldwide in tropical and subtropical waters. The melon-headed whale has been reported from the southern Caribbean, but not from the Gulf of Mexico.

Melon-headed whales reach a length of 2.6 to 2.7 m, with sexual maturity at about 2.3 m. Feeding habits are unknown, but the diet probably includes fish and squid.

Occurrence in the Study Area. Although melon-headed whales have not been reported from the Gulf of Mexico or the study area, their tropical/subtropical distribution suggests that they may occur in the study area.

References. Mitchell (1975); Leatherwood and Reeves (1983).

False Killer Whale (*Pseudorca crassidens*)

The **false killer whale** is distributed in tropical and warm temperate waters worldwide. This species often mass strands in large numbers. There have been several mass strandings on the east coast of Florida and along the Gulf of Mexico. There are no population estimates.

The maximum reported length of false killer whales is 6.1 m for males and 4.9 m for females. False killer whales are maintained in captivity, but most of the information on their biology comes from the examination of stranded animals. They feed on fish and cephalopods.

Occurrence in the Study Area. There have been two mass strandings of false killer whales in the study area (**Figure 8.3**). False killer whales may pass through the study area from time to time.

References. Moore (1953); Layne (1965); Caldwell and Caldwell (1973); Mitchell (1975); Odell et al. (1980); Schmidly (1981); Fritts et al. (1983); Leatherwood and Reeves (1983); Asper et al. (1988); Odell (in press).

Spotted Dolphins (*Stenella frontalis* and *Stenella attenuata*)

Spotted dolphins are widely distributed in tropical and some warm temperate waters. The systematics have recently been revised and two species proposed: *Stenella frontalis*, the Atlantic spotted dolphin; and *S. attenuata*, the pantropical spotted dolphin. *S. frontalis* includes *S. plagiodon*. *Stenella attenuata* includes those spotted dolphins referred to as bridled dolphins in the southeastern U.S. Both species of spotted dolphins occur in the waters of the southeastern U.S. and Gulf of Mexico. It is often difficult to distinguish the two species at sea or from a cursory examination of stranded specimens.

Both species of spotted dolphins reach an average length of 2.0 to 2.2 m, with males longer than females. Birth length is about 0.8 m. *Stenella attenuata* has been extensively studied in the eastern tropical Pacific, where average adult length varies between the stocks. Most of the information on spotted dolphins in the southeastern U.S. and Gulf of Mexico comes from stranded specimens. Seasonal migrations may occur (both north-south and inshore-offshore). The animals feed on epipelagic fish and epipelagic and mesopelagic squid.

Occurrence in the Study Area. Both species of spotted dolphins have stranded in the study area (**Figure 8.6**). They probably occur in deep waters regularly, but relative frequency of occurrence of the two species has not been determined.

References. Caldwell and Caldwell (1973); Mitchell (1975); Schmidly (1981); Fritts et al. (1983); Leatherwood and Reeves (1983); Perrin et al. (1987); Odell (in press).

Spinner Dolphins: Short-snouted Spinner Dolphin (*Stenella clymene*), and Long-snouted Spinner Dolphin (*Stenella longirostris*)

Spinner dolphins are slender animals whose common names are derived from their habit of spinning around the long axis of the body when they jump out of the water. Spinner dolphins average about 2 m in length, with males about 0.1 m longer than females. Average size varies between stocks. Long-snouted spinner dolphins are found worldwide in tropical, subtropical, and (sometimes) warm temperate waters. Short-snouted spinner dolphins are restricted to the Atlantic in similar waters. They generally occur in offshore waters where they feed on mesopelagic fish and epipelagic and mesopelagic squid. Mass strandings of both species have been known to occur.

Occurrence in the Study Area. Both species of spinner dolphins occur in the south-eastern Atlantic and Gulf of Mexico, but there is only one stranding record for each species in the study area (**Figure 8.7**). This was a mass stranding of a herd of short-snouted spinner dolphins and one long-snouted spinner dolphin. Both species may be expected to occur with unknown frequency in the offshore waters of the study area.

References. Mitchell (1975); Perrin et al. (1981); Schmidly (1981); Leatherwood and Reeves (1983); Odell (in press).

Striped Dolphin (*Stenella coeruleoalba*)

The **striped dolphin** is distributed worldwide from tropical to temperate waters. This dolphin is characterized by a distinct black stripe running from eye to anus. Maximum length is 2.7 m, with males slightly larger than females. Birth length is about 1 m.

Striped dolphins are highly gregarious and have been seen in herds of several thousand individuals. They feed primarily on mesopelagic fish but also eat squid. Food habits probably vary across the distribution range. Striped dolphins have stranded on both coasts of Florida, and live sightings have been made off both coasts. Some stocks migrate.

Occurrence in the Study Area. There have been strandings of striped dolphins in the study area. In addition, numerous live sightings have been made immediately northwest of the study area. It is reasonable to expect that they would be found in deep waters of the study area.

References. Layne (1965); Caldwell and Caldwell (1973); Mitchell (1975); Schmidly (1981); Fritts et al. (1983); Leatherwood and Reeves (1983); Odell (in press).

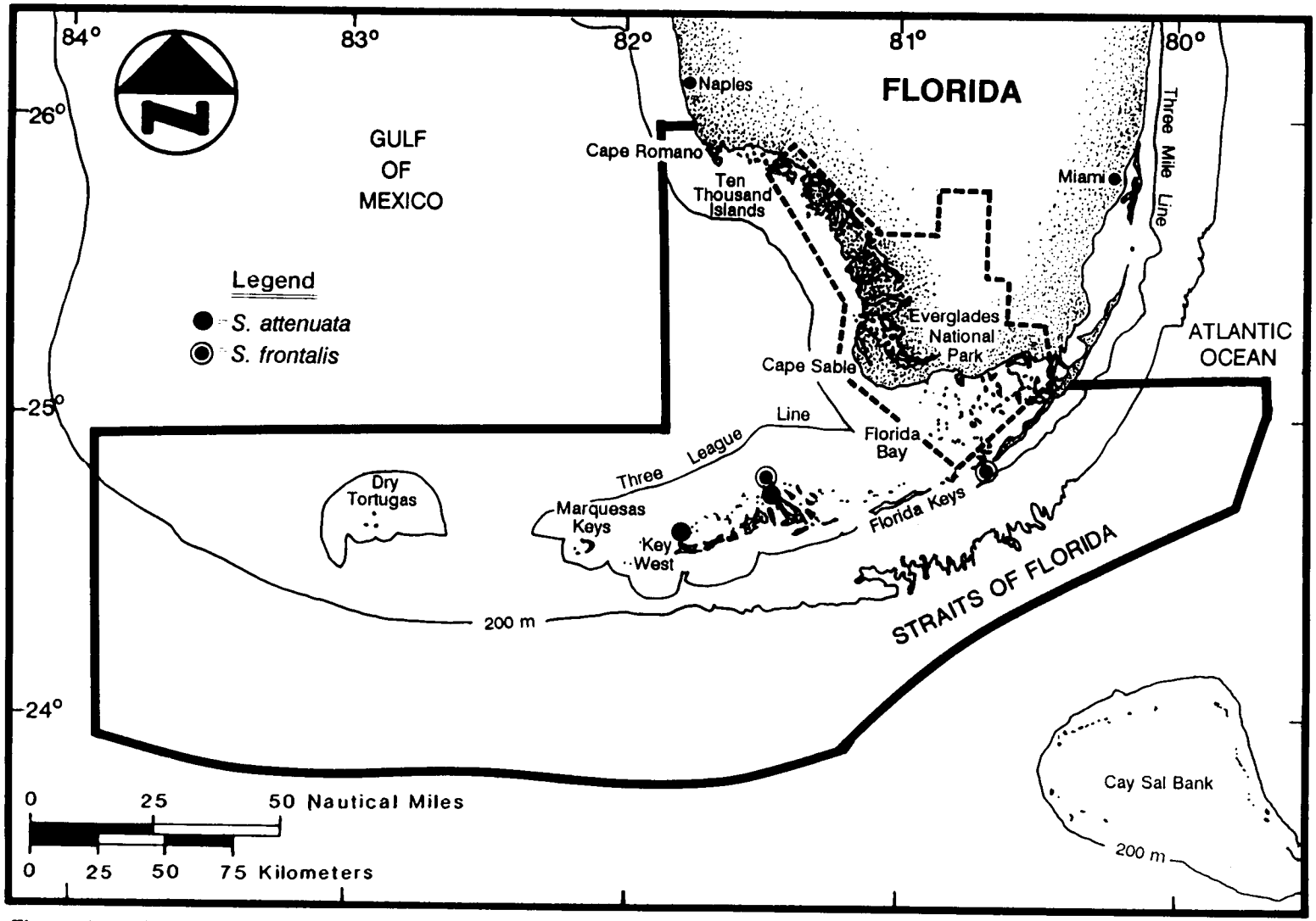

Figure 8.6. Approximate stranding locations in the study area for spotted dolphins (*Stenella attenuata* and *S. frontalis*).

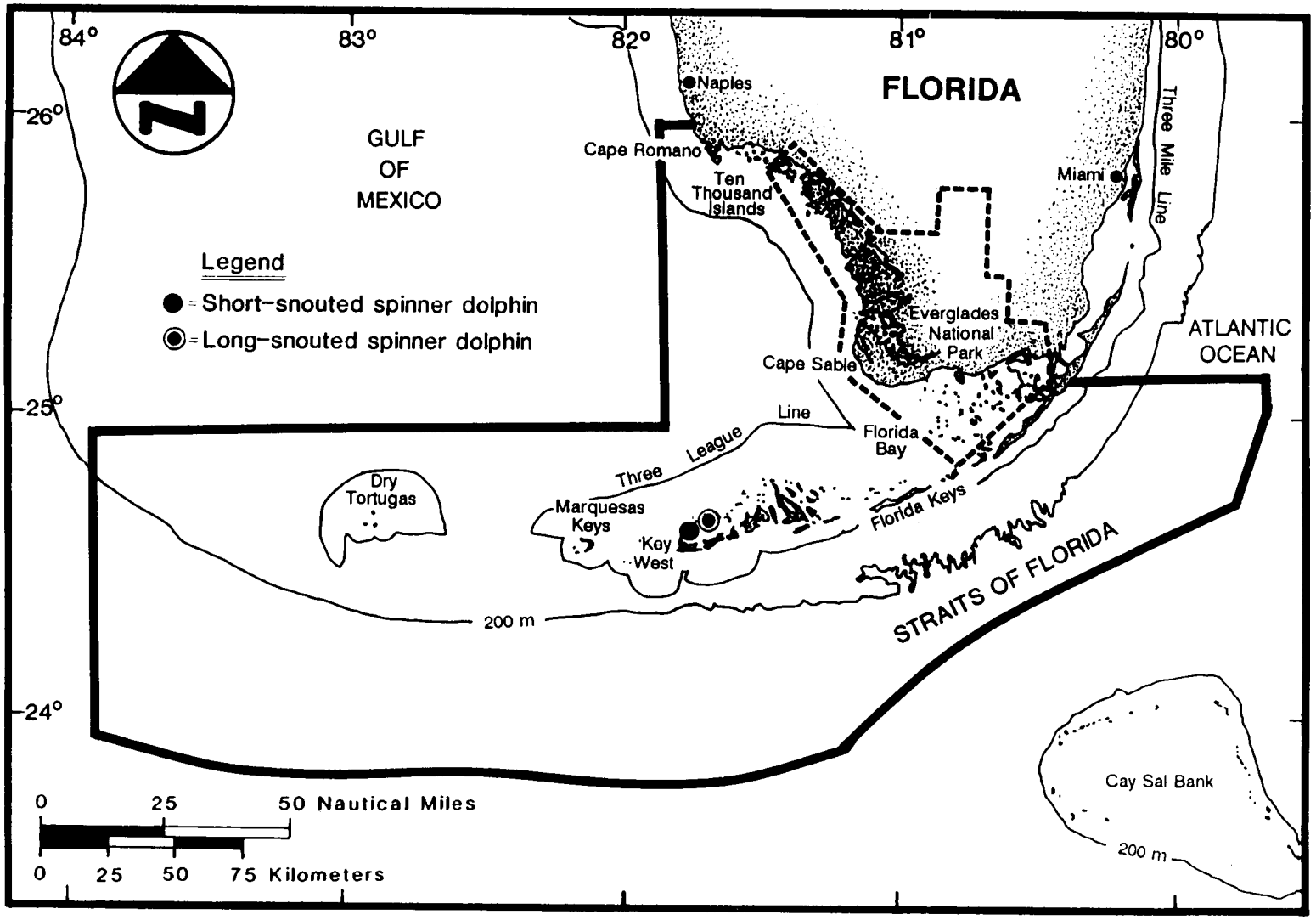

Figure 8.7. Approximate stranding locations in the study area for the short-snouted spinner dolphin (*Stenella clymene*) and the long-snouted spinner dolphin (*S. longirostris*).

Rough-toothed Dolphin (*Steno bredanensis*)

The **rough-toothed dolphin** is, in general, poorly known and appears to be widely distributed in tropical and subtropical waters. The species may reach a maximum length of 2.8 m. Birth length is not known.

Rough-toothed dolphins may occur in herds of several hundred, but smaller herds appear to be more common. They are known to mass-strand, and have stranded on both Atlantic and Gulf coasts of Florida. They likely occur in deep, offshore waters where they feed on fish, squid, and pelagic octopuses. Seasonal movements are unknown.

Occurrence in the Study Area. There have been two mass strandings of rough-toothed dolphins in the study area (**Figure 8.5**). They are likely to occur in deep waters of the study area, but with an unknown frequency.

References. Moore (1953); Layne (1965); Caldwell and Caldwell (1973); Mitchell (1975); Schmidly (1981); Leatherwood and Reeves (1983); Odell (in press).

Bottlenose Dolphin (*Tursiops truncatus*)

The **bottlenose dolphin** is distributed worldwide from tropical to temperate waters. It is found in shallow, inshore waters as well as deep, offshore waters. It is the most common cetacean in the study area (Scott et al. 1989), and based on its abundance, the most likely to be affected by oil and gas operations.

Systematics of *Tursiops* are confused, and several different species have been proposed. All are currently considered to be *T. truncatus* until a thorough evaluation has been made. There are two morphs: large and small. The small morph reaches an adult length of 2.5 to 2.6 m, whereas the large form may reach a length of 3.7 m. Birth length is about 1.2 m. *Tursiops* is the most common cetacean maintained in marine zoological parks and aquaria. It has been studied extensively in the field and in captivity.

Bottlenose dolphins are highly social and may form herds of over 100 animals. Smaller herds are more common. The animals feed on a wide variety of fish and some cephalopods. Migratory patterns are known in the temperate portions of the range. Both morphs of *Tursiops* are known from the east coast of Florida, and both forms appear to be present in the Gulf of Mexico. The small morph is predominant.

Occurrence in the Study Area. Bottlenose dolphins are common throughout the study area year-round. Almost all records are of the small morph. Estimates of average population size range from 1,723 to 3,916 animals, with the highest estimates during winter (Scott et al. 1989).

References. Moore (1953); Layne (1965); Mitchell (1975); Schmidly (1981); Leatherwood and Reeves (1982, 1983, 1990); Fritts et al. (1983); Asper et al. (1988); Scott et al. (1989); Odell (in press).

Blainville's Beaked Whale (*Mesoplodon densirostris*)

Blainville's beaked whale is, as is the case for most beaked whales, poorly known. It occurs widely from tropical to warm temperate waters. This whale reaches a length of about 4.7 m. The single pair of mandibular teeth erupt in the males but not in the females. Birth length is unknown.

Blainville's beaked whales seem to be relatively solitary and inhabit deep waters, where they feed on cephalopods. Seasonal movements are not known.

Occurrence in the Study Area. Blainville's beaked whales are known from strandings in the Gulf of Mexico and the Atlantic coast of Florida, but not from the study area. It is likely that they occur in the study area from time to time.

References. Moore (1953); Layne (1965); Mitchell (1975); Schmidly (1981); Fritts et al. (1983); Leatherwood and Reeves (1983); Mead (1989); Ridgway and Harrison (1989); Odell (in press).

Sowerby's Beaked Whale (*Mesoplodon bidens*)

Sowerby's beaked whale is extremely rare and is known in the southeastern U.S. from only one record from the Florida Panhandle in the Gulf of Mexico. This species reaches a length of at least 5 m and generally occurs in cold waters of the North Atlantic. The Gulf of Mexico record is the southernmost record for the species in the western North Atlantic. There are no population estimates, and seasonal movements are unknown.

Occurrence in the Study Area. There are no records for Sowerby's beaked whales in the study area. However, because of the record from the Gulf of Mexico, this species might be expected to pass through the study area.

References. Mitchell (1975); Leatherwood and Reeves (1983); Bonde and O'Shea (1989); Mead (1989); Odell (in press).

Gervais' Beaked Whale (*Mesoplodon europaeus*)

Gervais' beaked whale is known primarily from the western North Atlantic from tropical to warm temperate waters, with a few records from the western North Atlantic and the northern South Atlantic. The species may reach an adult length of 5 m. Birth length is about 2 m. As with other beaked whales, the mandibular teeth erupt only in the males.

Gervais' beaked whales favor deep waters, where they feed on cephalopods. Seasonal movements are unknown, and there are no population estimates.

Occurrence in the Study Area. Gervais' beaked whales have stranded in the study area (**Figure 8.8**) and probably occur in deep waters at an unknown frequency.

References. Moore (1953); Layne (1965); Mitchell (1975); Leatherwood and Reeves (1983); Mead (1989); Ridgway and Harrison (1989); Odell (in press).

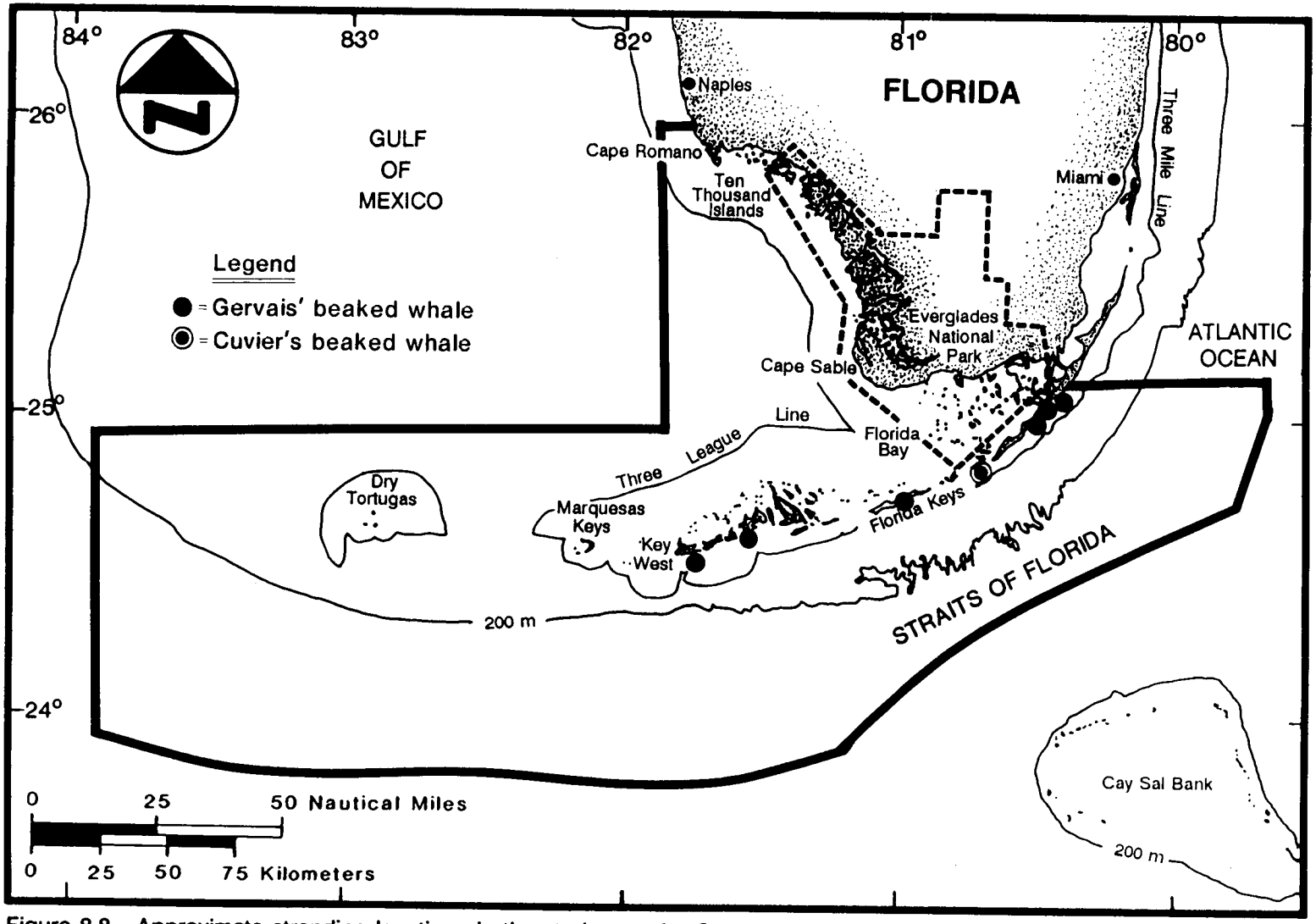

Figure 8.8. Approximate stranding locations in the study area for Gervais' beaked whale (*Mesoplodon europaeus*) and Cuvier's beaked whale (*Ziphius cavirostris*).

True's Beaked Whale (*Mesoplodon mirus*)

True's beaked whale is extremely rare and is known only from the temperate Atlantic and southwestern Indian Ocean. There are several records from North Florida through the Carolinas. There are no records from the Gulf of Mexico. This species reaches a length of 5 to 5.5 m. The single pair of mandibular teeth erupt only in the male.

True's beaked whales probably feed on cephalopods. There are no population estimates, and seasonal movements are unknown.

Occurrence in the Study Area. There are no records for True's beaked whales in the study area. However, as with *Mesoplodon bidens*, this species might be expected only on rare occasions.

References. Moore and Wood (1957); Mitchell (1975); Schmidly (1981); Leatherwood and Reeves (1983); Mead (1989).

Cuvier's Beaked Whale (*Ziphius cavirostris*)

Cuvier's beaked whale is found in all oceans from tropical to subpolar waters. It may reach a length of 7.5 m. Sexual maturity is at about 6 m in females and 5.5 m in males. Birth length is about 2.7 m. The single pair of teeth are located at the tip of the mandibles and erupt only in the males.

Cuvier's beaked whales may be found in herds of a few individuals. These whales inhabit deep waters and feed on cephalopods and deepwater fish. There are no population estimates. Seasonal movements may occur in the subpolar regions of their distribution.

Occurrence in the Study Area. Cuvier's beaked whales have stranded in the study area (**Figure 8.8**). They may be expected to occur with a low frequency in deep waters at any time of year.

References. Moore (1953); Layne (1965); Mitchell (1975); Schmidly (1981); Fritts et al. (1983); Leatherwood and Reeves (1983); Heyning (1989); Ridgway and Harrison (1989); Odell (in press).

Florida Manatee (*Trichechus manatus latirostris*)

The **Florida manatee** is a distinct subspecies of the West Indian manatee (*Trichechus manatus*), which is classified as an Endangered species. *Trichechus manatus* occurs from the southeastern U.S. to northeastern Brazil; *T. m. latirostris* is found from Virginia and the Carolinas to Texas. The Florida manatee may reach a length of 3.9 m and weigh 1,500 kg; the average manatee is about 3 m long. Birth length is about 1.2 m. Sexual maturity is reached at about 2.75 m in both sexes. Gestation lasts about one year.

Manatees are herbivores and feed extensively on seagrasses and freshwater vegetation. Their distribution is limited by the distribution of seagrasses, the possible need for fresh water, and temperature. Manatees generally move south along the Florida peninsula in fall and winter, and north in spring and summer. They can be found in peninsular Florida year-round. The minimum population count in winter 1986 was 1,200 individuals. Neither the size nor the trend of the Florida manatee population is known. Collisions with power boats currently account for at least 35 to 40% of total annual mortality (about 120 animals) in Florida. The number of manatees killed by power boats has increased rapidly in recent years and parallels the trend of an increasing boat population.

Occurrence in the Study Area. Manatees have been documented in the study area in Florida Bay and westward as far as the Dry Tortugas (**Figure 8.9**). They can be expected in areas of seagrass abundance on a year-round basis. No calving or congregating sites have been identified within the study area.

References. Moore (1953); Layne (1965); Odell (1982); Fritts et al. (1983); Leatherwood and Reeves (1983); Reynolds and Ferguson (1984); Domning and Hayek (1986); Van Meter (1987); Odell (in press).

SEA TURTLES

Background

Sea turtles belong to the ancient Order Testudinata. They occur primarily from tropical to temperate seas. They generally occur nearshore, but some (e.g., the leatherback) may occur regularly in deep oceanic waters and dive to great depths. Most sea turtles are carnivores and feed on a variety of invertebrates. Green turtles, particularly juveniles and older, feed heavily on seagrasses, which places them in a niche that overlaps somewhat with that of the sirenians.

The five sea turtle species that may occur in the study area are listed in **Table 8.2.** Endangered/Threatened status is indicated in the table. Descriptions of each species are provided below.

Species Accounts

Green Sea Turtle (*Chelonia mydas*)

The **green sea turtle**, an Endangered species, is a medium-to-large turtle with a carapace length of 76 to 153 cm. The carapace is oval in shape, pointed posteriorly, and extremely variable in coloration. This variability in coloration can lead to confusion with other marine species, especially loggerheads. The head ranges from 12 to 15 cm wide in adults. Adult green turtles weigh about 150 kg. The limbs are long and paddle-like. Skin coloration is similar to that of the carapace with a yellowish tint. Males have longer tails than females.

Table 8.2. Sea turtles that are known to occur in the study area.

Species	Common Name	Figure No.*	Status†	
			Federal	State
TESTUDINATA				
Cheloniidae				
Chelonia mydas	green sea turtle	–	T§	E
Caretta caretta	loggerhead sea turtle	8.10	T	T
Lepidochelys kempi	Kemp's ridley sea turtle	–	E	E
Eretmochelys imbricata	hawksbill sea turtle	–	E	E
Dermochelyidae				
Dermochelys coriacea	leatherback sea turtle	–	E	E

* Refers to figures in this chapter showing locations of strandings in the study area.
† E = Endangered; T = Threatened.
§ The Florida nesting population of *C. mydas* is considered Endangered by the U.S. Fish and Wildlife Service.

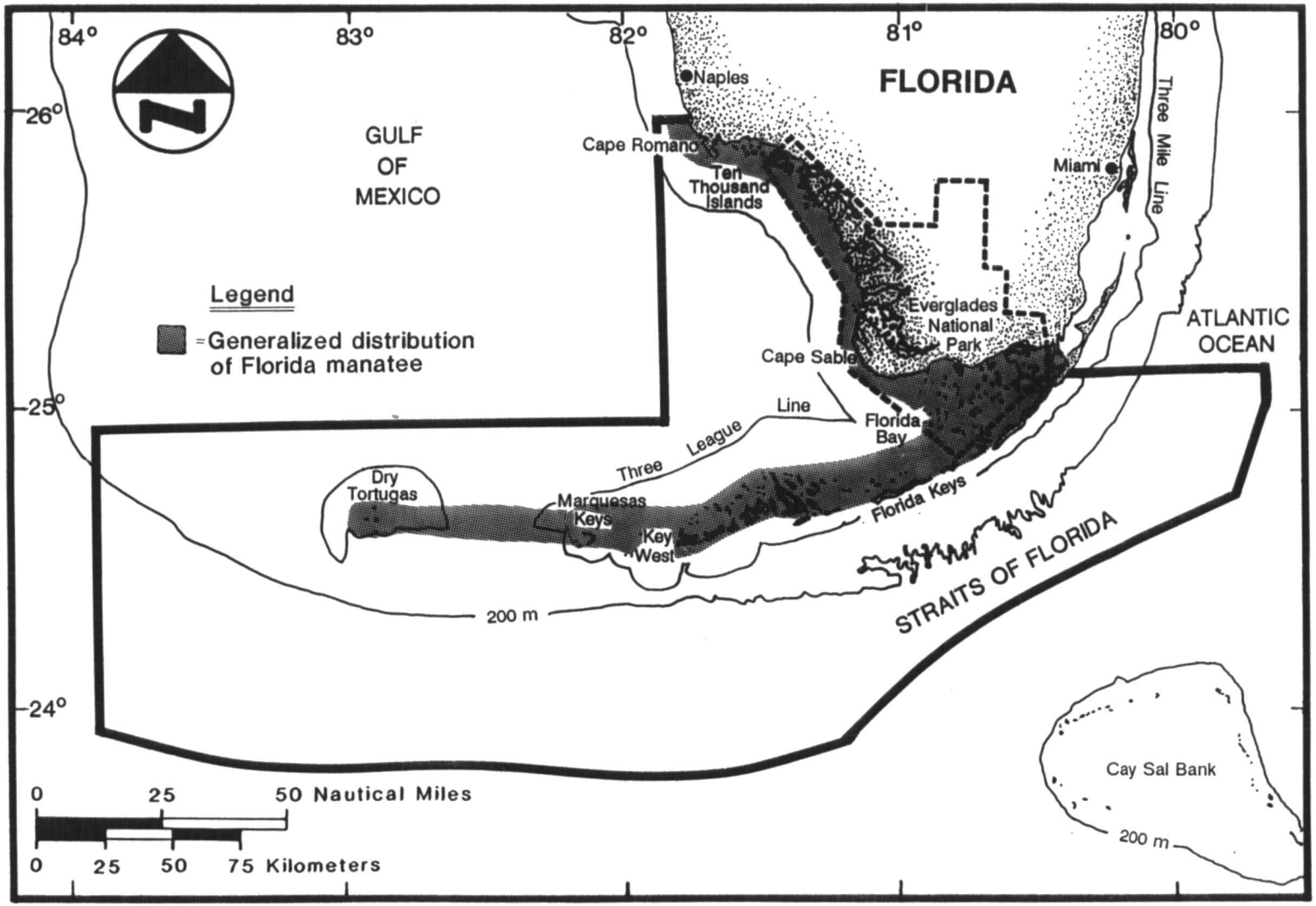

Figure 8.9. Generalized distribution of the Florida manatee (*Trichechus manatus latirostris*) in the study area.

Green sea turtles are widely distributed between 35°N and 35°S. They have been recorded as far north as Massachusetts. They are common in Bermuda, reaching south to the Argentine coast at Mar del Plata and Necochea. In the Pacific, green turtles are abundant as far north as southern California and south to southern Chile. They are also found in great numbers on the coasts of Nicaragua and Costa Rica.

Green sea turtles are thought to feed on marine invertebrates during the first year of life. Larger turtles frequent shallow-water seagrass flats to feed on vegetation. A subadult green sea turtle was reported to have a large quantity of fish eggs in the gut. Seagrass beds in Monroe County waters represent important feeding habitat for the species.

Green sea turtles mate offshore from the nesting beaches. Females come ashore several times during a season to lay eggs (about 110 per nest) in the sand. The incubation period is 48 to 70 days. Hatchlings are suspected to be pelagic and associate with *Sargassum* rafts. Age at maturity depends on growth rate. Maturity may be from 8 to 13 years in temperate climates, or at a carapace length of 80 cm. The nesting season varies considerably from one area to another. In some areas, the nesting season is restricted to a few months of the year, whereas in other locales nesting occurs year-round with one or two peaks of a few months. Year-round seasons occur in Malaya, Sarawak, the Gulf of Siam, and the Seychelles. In Florida, the breeding/nesting season is from April to July. Green turtle nests have been reported on east coast beaches from Volusia County south through Monroe County.

Occurrence in the Study Area. Green turtles have not nested in the study area in recent years. However, the species does occur in the waters of the study area and is known to feed there.

References. True (1884); Carr (1952); Carr and Ingle (1959); Rebel (1974); Bjorndal (1982); Dodd (1982); Zieman (1982); Harris et al. (1984); Van Meter (1986); Conley and Hoffman (1987); Ogren et al. (1989); Scott et al. (1989).

Loggerhead Sea Turtle (*Caretta caretta*)

The **loggerhead sea turtle**, a Threatened species, is a large turtle, with a carapace size averaging about 100 cm in length. The head is large relative to the body, averaging 14 to 26 cm wide. Adult loggerheads weigh from 90 to 160 kg. The carapace is an elongated oval and reddish-brown in color. The carapace is often covered with epizoans and algae, more so than other species, thus making the turtle appear lighter in color than it actually is. As in all turtles, the male has a proportionately longer tail.

Loggerhead turtles are found all over the world, inhabiting continental shelves, bays, lagoons, and estuaries in the temperate, subtropical, and tropical waters of the Atlantic, Pacific, and Indian Oceans.

Loggerhead turtles are omnivorous, but prefer a carnivorous diet. They eat shellfish--especially clams, crabs, and oysters. Their prey are bottom-dwelling organisms; loggerheads have been observed at depths of 30 m and may be able to dive 50 to 70 m.

Loggerheads nest worldwide, with major nesting grounds generally located in warm temperate and subtropical regions. In mainland Florida, loggerheads nest from April through September; in the Florida Keys, the breeding season is from April through June. There is a significant amount of loggerhead nesting in Everglades National Park.

Loggerheads mate at the surface of the water offshore near the nesting beaches, before and during the nesting season. Nesting usually occurs at night, but diurnal nesting does occur. Several times a season the female comes ashore and lays an average of 110 eggs. The incubation period is from 50 to 70 days.

Few data exist on hatchlings at sea. Some are found in association with *Sargassum* rafts. Age at maturity varies with growth rate. In captivity, females reach egg-laying size in 6 to 7 years. In the wild, animals mature at a carapace length of 79 cm.

Occurrence in the Study Area. Loggerheads are the only sea turtles that nest in the study area (**Figure 8.10**). They may be sighted year-round in the study area.

References. Carr (1952); Rebel (1974); Davis and Whiting (1977); Pritchard (1979); Fritts and Reynolds (1981); Bjorndal (1982); Fritts et al. (1983); Harris et al. (1984); Van Meter (1986); Conley and Hoffman (1987); Dodd (1988); Ogren et al. (1989); Scott et al. (1989).

Kemp's Ridley Sea Turtle (*Lepidochelys kempi*)

The **Kemp's ridley** is the smallest and most Endangered of the sea turtles. Its carapace often appears round, with a length of 50 to 70 cm, and a width almost the same. It has a proportionately wide head, about 14 cm. Adults typically weigh about 40 to 45 kg. The limbs are paddle shaped. The adult Kemp's ridley ranges from a slate to a pale gray in color; young are darker, often near black. The males have proportionately long tails.

Kemp's ridley turtles are found along the Gulf coasts of Mexico, Texas, Louisiana and Florida. They are regularly sighted in the Keys and the Florida east coast, and occasionally in Georgia and north to New England (Van Meter 1986). They are absent in the Caribbean.

Kemp's ridley sea turtles feed on crustaceans, molluscs, jellyfish, and fish. They are mostly bottom feeders. The coastal areas of the Gulf of Mexico, especially around Louisiana, are important feeding grounds.

Mating of Kemp's ridleys occurs offshore of the nesting beaches. Kemp's ridley turtles nest in aggregations called "arribadas," almost exclusively in Mexico. Most of the nesting occurs within a small stretch of beach north of Tampico. These arribadas occur at irregular times between April and June. The females come ashore three times a season to lay an average of 110 eggs. Kemp's ridleys nest during daylight, unlike other sea turtle species (Rebel 1974). The eggs incubate in 50 days. Kemp's ridley turtles reach sexual maturity at a carapace length of about 58 cm, at which length they are at least 5.5 years old.

Occurrence in the Study Area. There are no Kemp's ridley nesting sites in the study area. However, the animals do occur in the study area.

References. Carr (1952); Rebel (1974); Bjorndal (1982); Fritts et. al (1983); Van Meter (1986); Caillouet and Landry (1989); Ogren et al. (1989).

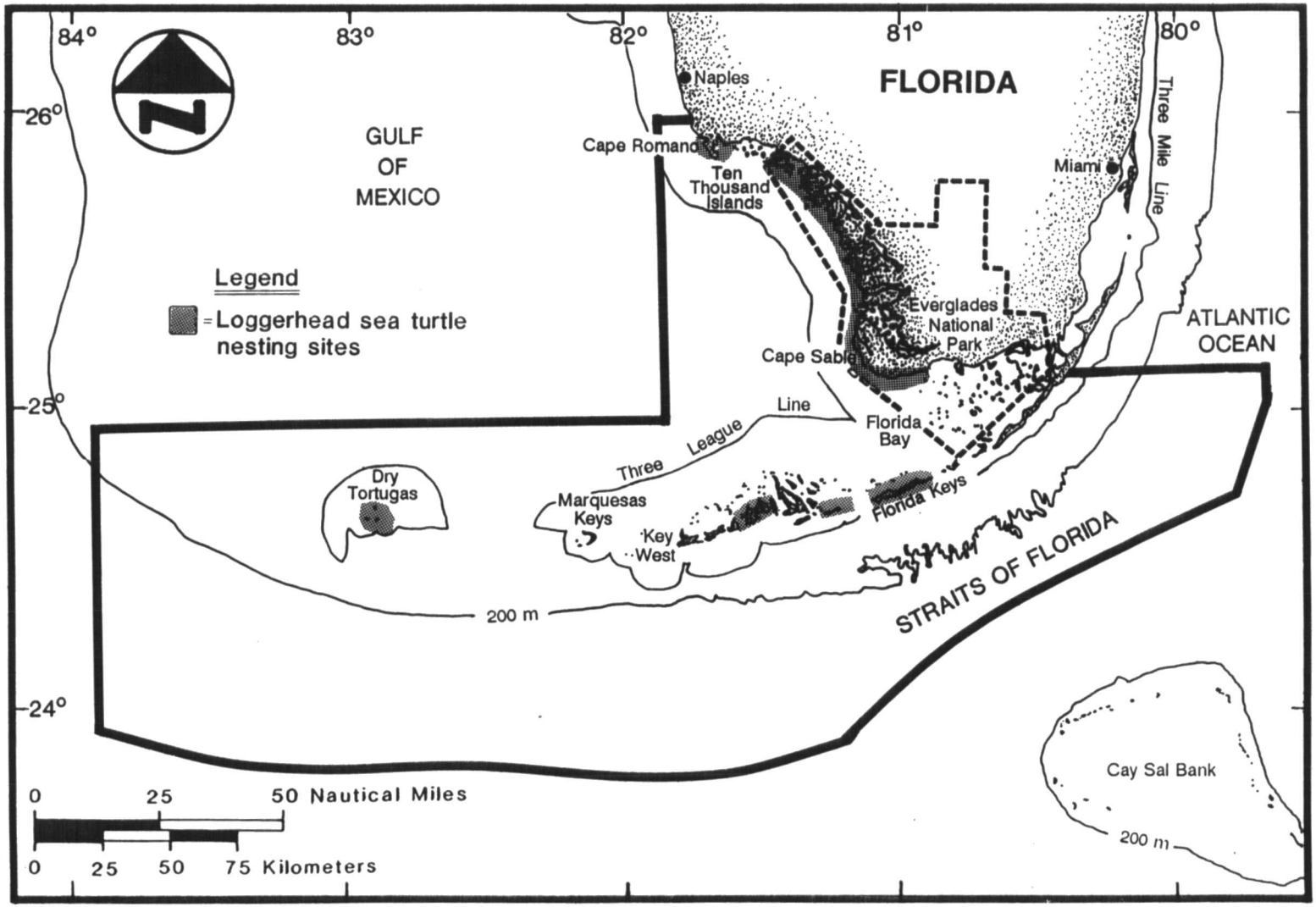

Figure 8.10. Approximate locations of nesting sites of the loggerhead sea turtle (*Caretta caretta*) in the study area.

Hawksbill Sea Turtle (*Eretmochelys imbricata*)

The **hawksbill sea turtle**, another Endangered species, is smaller than the green sea turtle, with a carapace of <100 cm in length. Maximum weight is about 363 kg. The carapace of adults is amber with streaks and markings of reddish brown, blackish brown, and yellow. The plastron is whitish yellow, often with a few black splotches. Young are usually black or brownish black with light brown on the keels, margins of shell and flipper, and upper outer areas of the neck. Males have longer tails than females. Limbs are paddle-shaped, each equipped with two claws.

Hawksbill sea turtles are found throughout the world in tropical waters, especially near coral reefs and rocky outcroppings in shallow coastal areas. They are present throughout the Caribbean and are rarely found north of Florida.

Hawksbill sea turtles are omnivorous. Within two days of hatching, they eat seagrasses. Later, the diet includes algae, barnacles, fish, and jellyfish. The adult diet is primarily sponges, sea urchins, and ectoprocts.

Hawksbill sea turtles breed in warm water between 25°N and 25°S. Copulation takes place nearshore; eggs are laid in sand of fine, gravelly beaches. Nests are about 43 cm deep and 25 cm in diameter. Average clutch size is about 160; average size of nesting females is about 84 cm in carapace length. Average incubation time is 58.6 days.

Occurrence in the Study Area. Hawksbill sea turtles occur and feed in the study area, but they do not nest there. Frequency of occurrence is unknown.

References. Carr (1952); Carr et al. (1966); Rebel (1974); den Hartog (1980); Bjorndal (1982); Van Meter (1986); Ogren et al. (1989).

Leatherback Sea Turtle (*Dermochelys coriacea*)

The Endangered **leatherback sea turtle** is the largest of the sea turtles, with a carapace length of about 180 cm and a weight of up to 590 kg. The leatherback has a shield-shaped carapace with seven prominent ridges running from front to back. The carapace and extremities lack scutes; rather, they are covered with smooth skin. The front flippers are very long. The leatherback is generally black above and marked with pale spots. Ventrally, it is white with black mottlings.

Leatherback sea turtles range throughout the Atlantic, Pacific, and Indian Oceans. They have been found as far north as Labrador and Alaska and as far south as Chile and the Cape of Good Hope. Leatherback turtles spend much time far out at sea, but they also concentrate in relatively shallow coastal waters, including the east and west coasts of Florida.

Jellyfish are the primary food of leatherback turtles. They are also known to eat the animals that live in association with jellyfish. Fish remains and hatchling ridleys have been reported in leatherback stomachs. The presence of deepwater jellyfish species in the stomachs of leatherback sea turtles indicates that they are capable of diving to great depths.

Leatherback turtles nest in tropical and subtropical mainland shores, especially in Malaysia, Mexico, the U.S. Virgin Islands, Central America, and the Guianas. Some nest in Florida and Georgia. There are no records of nesting on the beaches of the

Florida Keys. A major nesting area was discovered recently along the southern Mexican Pacific shoreline, where it was estimated that there were 100,000 breeding females. Leatherback sea turtles mate away from their nesting beaches. A male may mate with females from several nesting beaches. Leatherbacks are less faithful to a nesting beach than other species of sea turtles. They nest at night at 10-day intervals, about six to seven times a season. Females nest every two to three years. From 60 to 100 eggs are laid per clutch. Leatherbacks lay fewer eggs than other sea turtles, but both the eggs and the hatchlings are larger. The incubation period is from 60 to 70 days.

Occurrence in the Study Area. Leatherback sea turtles occur in deep waters of the study area with unknown frequency. There are no nesting records.

References. Carr (1952); Yerger (1965); Pritchard (1971, 1979, 1982); den Hartog (1980); Hirth (1980); Bjorndal (1982); Hopkins and Richardson (1984); Van Meter (1986); Ogren et al. (1989).

ENVIRONMENTAL ISSUES

General

Worldwide, marine mammals and sea turtles have been, and continue to be, affected by various forms of environmental pollution (e.g., chlorinated hydrocarbons, heavy metals, plastics) and environmental degradation (e.g., coastal development). Increasingly, these animals have become victims of commercial fishing activities (e.g., purse seining, drift gillnetting, shrimp trawling).

Historically, marine mammals and sea turtles have been exploited and overexploited by humans for food, hides, meat, oil, and bone. Some populations of marine mammals and sea turtles were reduced to levels from which recovery was thought to be impossible (e.g., the blue, gray, and right whales, and the elephant seal). The Caribbean monk seal was in fact completely eliminated by human activities (hunting). Some species, such as the gray whale and the elephant seal, have made spectacular recoveries to population levels at or exceeding pre-exploitation levels as a result of total protection from hunting. The verdict is still out on other species (blue and right whales) which, even though fully protected, have not recovered at the anticipated rate. Changes in the food web structure of entire ecosystems may be partly responsible. For example, depletion of blue whale stocks in the Antarctic resulted in a surplus of krill that could be exploited by other predators. The crabeater seal population apparently expanded as a result of this surplus. Other animal populations probably responded similarly if they were food-limited. The result is that, even though blue whales are fully protected, there may not be enough surplus food for the population to recover to previous levels. In other areas (e.g., the Bering Sea), human fisheries compete directly with marine mammals for the same prey species.

Even though marine mammals and sea turtles are fully protected within U.S. waters, human activities other than hunting are directly and indirectly affecting them. A major factor is incidental take in fisheries. Thousands of marine mammals are killed each year in tuna purse seines and salmon gill nets in the North Pacific and drift nets worldwide; others die due to entanglement in lost or discarded fishing gear. The possibility of expanded use of drift gillnets along the U.S. east coast is cause for alarm. Sea turtles are killed in shrimp trawls and become entangled in discarded fishing gear. Henwood and Stuntz (1987) estimated that the southeastern U.S. shrimp fishery kills over 11,000 sea turtles each year (prior to the implementation of turtle excluder devices), with about 10,000 of these being loggerheads.

Pollution also takes its toll of marine mammals and sea turtles. Various chemical pollutants (pesticides, polychlorinated biphenyls, and trace metals) accumulate in the tissues of these animals, with as yet unknown effects. Marine mammals and sea turtles ingest discarded plastic material, which has been directly responsible for the death of some animals (Sadove and Morreale 1989).

Marine mammals and sea turtles are often hit by boats and severely injured or killed. Many of the right whales that migrate through the coastal waters of the eastern U.S. have been hit by ships. For example, 60% of the right whales in the New England Aquarium's photographic identification catalog show evidence of having been hit by ships or their propellers (NMFS 1989).

Study Area

The West Indian manatee (througout its range) is currently Endangered as the result of historic overhunting for meat, fat, bone, and hides. The manatee has a low reproductive rate (one calf every three years; sexual maturity at about eight years of age). Although the species is protected througout its range, other human activities in Florida have replaced hunting as a threat, and these continue to prevent recovery of the population. Almost all of the manatees have been hit by a boat at one time or another. About one-third of total annual manatee mortality in Florida is directly attributable to boat collisions, and about half of total mortality is due to human factors (including boats). Collisions with boats (propeller and hull impact) have increased dramatically during the last five years (Florida Department of Natural Resources, unpubl. data).

Other human-related factors affecting manatees include entrapment in flood control dams and navigation locks, ingestion of plastic debris and lost fishing lures, entanglement in crab-pot float lines and lost monofilament line, and limited poaching and vandalism. Destruction of manatee habitat (particularly seagrass beds) as a result of coastal development is an ever-increasing threat to the continued existence of manatees in Florida. In addition, manatees are subject to mortality as a result of unusually cold weather (as during the freeze of December 1989) and as a result of red tide toxin. These unpredictable natural factors add to the high mortality rate.

The bottlenose dolphin is the most common marine mammal in the waters of the southeastern U.S. and the Gulf of Mexico. The species is affected to an unknown extent by commercial fishing activities. Dolphins have been found entangled in gillnets and other fishing gear (Odell, unpubl. data). Carcasses have also been found with flukes cleanly cut off, suggesting removal from net entanglements (Odell, unpubl. data). Some dolphins have also been shot. These factors have not been quantified because beached dolphins are not thoroughly examined. Bottlenose dolphins are a top-level predator and do accumulate pollutants, such as chlorinated hydrocarbons. Factors (such as pollution) that affect dolphin prey will ultimately affect these animals as well. Recently, Geraci (1989) reported that over 700 bottlenose dolphins died over a nine-month period between New Jersey and east central Florida, apparently as a result of ingestion of fish contaminated with brevetoxin.

The other marine mammal species known or suspected to occur in the study area are (apparently) relatively rare in comparison with the bottlenose dolphin. However, large whales (blue whale, humpback whale, right whale, etc.) are subject to entanglement in fishing gear and collisions with vessels. Pygmy sperm whales are known to accumulate chlorinated hydrocarbons and can die from ingesting plastic bags. Humpback whales are subject to saxitoxin poisoning from eating contaminated fish (Geraci et al.

1989). It is therefore reasonable to assume that increased pollution, fishing activities, and ship traffic would affect these animals.

The greatest single threat to sea turtles in the southeastern U.S. and the Gulf of Mexico is death in commercial shrimp trawls. The effect of regulations requiring the use of turtle excluder devices has yet to be evaluated. Destruction of nesting beaches through coastal development is a second major threat to sea turtles. In addition, sea turtles may die from ingestion of plastic debris, entanglement in lost fishing gear, and collisions with vessels. Although the Threatened loggerhead sea turtle is the species most commonly killed in shrimp trawls and found dead on the beaches, the other Endangered sea turtles (particularly the Kemp's ridley) suffer proportionately greater mortality. Human activities that affect seagrass beds and other components of sea turtle habitats continue to work against the survival of these species. There is little published information on the accumulation of pollutants (chlorinated hydrocarbons, heavy metals, etc.) in sea turtles.

CONCLUSIONS

Marine Mammals

Nineteen species of marine mammals are known from the study area, and 10 additional species may occur there, based on strandings and sightings in nearby waters. Of the 19 known species, only three (the bottlenose and Risso's dolphins and the Florida manatee) are known from sightings of live, non-stranded animals. For those species known only from strandings, one can only speculate about existing and potential threats (natural and anthropogenic) based on observations made outside the study area. Several of those threats have been discussed in the preceding section.

Almost all of the information on marine mammals in the study area comes from strandings, not sightings. If potential threats to these species from oil and gas operations are to be evaluated, the basic facts about their distribution and ecology in the study area need to be known. It is not possible to detail potential effects or to say that there will be no effects, without more information. For example, the potential for accumulation of trace metals in the pygmy sperm whale cannot be evaluated until it is known whether the species even feeds in the area.

Data on the distribution, abundance, and ecology of marine mammals in the study area are nearly or completely lacking. The exceptions are aerial seasonal distribution and abundance data from aerial surveys for bottlenose dolphins (Scott et al. 1989) and aerial survey data for manatees and bottlenose dolphins within the waters of Everglades National Park (Odell, unpubl. data).

The data base on marine mammals could be improved by compiling existing survey data, then conducting extensive aerial and shipboard surveys to assess seasonal distribution and abundance patterns. Two marine mammal and sea turtle workshops sponsored by the Minerals Management Service (Keller and Adams 1983; Hain 1990) recommended aerial surveys as one of the best ways to document the distribution and abundance of these animals in the Gulf of Mexico. Recent work by Scott et al. (1989) clearly demonstrates the value of these surveys.

Over the long term, aerial survey results could be used to plan additional, detailed studies (e.g., using radio or satellite tracking) of individual species. If, for example, pygmy sperm whales were found to occur in deep waters of the study area on a regular

basis, a study involving radio telemetry could be useful to determine how they use the habitat, thereby increasing our ability to predict potential effects of human activities.

Because the bottlenose dolphin occurs year-round and in high numbers in the study area, it is the species most likely to be affected by human activities in the marine environment. Detailed studies of its seasonal distributional patterns, movements of individuals, calving areas, and feeding habits should be undertaken.

Because the Florida manatee is the only Endangered species of marine mammal known to reside in the study area, its distribution and abundance should be documented through aerial surveys, and its movement should be studied using radio and/or satellite tracking. Specific attention should be given to the delineation of manatee feeding areas within the study area.

Sea Turtles

The loggerhead sea turtle is the most common sea turtle species in the study area, and the only one that nests there. The green, hawksbill, Kemp's ridley, and leatherback turtles occur to a lesser, but mostly unknown, extent. Sea turtle populations are being affected by mortality in commercial shrimp trawls. The animals ingest plastic and become entangled in lost fishing gear, and their nesting beaches are continually threatened by development.

The Kemp's ridley is the most Endangered of the sea turtle species. Effects of human activities such as shrimp trawling are proportionately greater on this species than on others such as the loggerhead sea turtle. Consequently, decisions about new human activities in the marine environment must carefully evaluate the possibility of additional mortality on this species.

Little is known of the distribution, abundance, and ecology of sea turtles in the study area. As with most of the marine mammals, this severely limits our ability to predict consequences of new human activities. Additional aerial surveys need to be conducted to determine seasonal distribution and abundance patterns. These could be followed up by telemetry studies to determine patterns of habitat use by the various species.

Endangered and Threatened Species

The Endangered Florida manatee and the Threatened loggerhead sea turtle are the most common of the Endangered and Threatened species that occur in the study area. They can be found year-round and are the species that are most likely be affected by human activities in the marine environment. The other Endangered species of cetaceans known from the study area (fin and sperm whales) are, as far as we know based on strandings, relatively uncommon. The sperm whale may feed in deep waters of the study area. Data are insufficient for further speculation. The remaining Endangered/ Threatened sea turtles that are known from the study area (green, hawksbill, leatherback, and Kemp's ridley) are probably more common (in general) than the fin or sperm whales. Other Endangered cetaceans known from the Gulf of Mexico (blue, humpback, right, and sei whales) may pass through the study area.

REFERENCES CITED

Anon. 1986. *Report of the southeastern U.S. right whale workshop*. Savannah: The Georgia Conservancy.

Asper, E. D., L. H. Cornell, D. A. Duffield, and N. Dimeo-Ediger. 1988. Marine mammals in zoos, aquaria and marine zoological parks in North America: 1983 census report. *Int. Zoo Yrbk.* 27:287-294.

Bjorndal, K. A., ed. 1982. *Biology and conservation of sea turtles. Proceedings of the world conference on sea turtle conservation*, Washington, DC, 26-30 November 1979. Washington, DC: Smithsonian Institution Press.

Bonde, R. K., and T. J. O'Shea. 1989. Sowerby's beaked whale (*Mesoplodon bidens*) in the Gulf of Mexico. *J. Mammal.* 70(2):447-449.

Brownell, R. L., Jr., P. B. Best, and J. H. Prescott, ed. 1986. *Right whales: Past and present status*. Rep. Int. Whal. Comm. (Special Issue 10).

Caillouet, C. W., Jr., and A. M. Landry, ed. 1989. *Proceedings of the First International Symposium on Kemp's Ridley Sea Turtle Biology, Conservation, and Management*. Texas A&M Univ. Sea Grant College Publ. No. 89-105. College Station, TX.

Caldwell, D. K., and M. C. Caldwell. 1973. Marine mammals of the eastern Gulf of Mexico. In *A summary of knowledge of the eastern Gulf of Mexico*, ed. J. I. Jones et al., III-I-1 to III-I-23. St. Petersburg: Florida Institute of Oceanography.

Caldwell, D. K., and M. C. Caldwell. 1989. Pygmy sperm whale *Kogia breviceps* (de Blainville, 1838): Dwarf sperm whale *Kogia simus* Owen 1866. In *Handbook of marine mammals, vol. 4. River dolphins and the larger toothed whales*, ed. S. H. Ridgway and R. Harrison, 235-260. London: Academic Press.

Carr, A. F. 1952. *Handbook of turtles. The turtles of the United States, Canada and Baja California*. Ithaca, NY: Cornell Univ. Press.

Carr, A. F., and R. M. Ingle. 1959. The green turtle (*Chelonia mydas*) in Florida. *Bull. Mar. Sci. Gulf Caribb.* 9:315-320.

Carr, A. F., H. Hirth, and L. Ogren. 1966. The ecology and migrations of sea turtles, 6. The hawksbill turtle in the Caribbean Sea. *Am. Mus. Novit.* 2248.

Conley, W. J., and B. A. Hoffman. 1987. Nesting activity of sea turtles in Florida, 1979-1985. *Fla. Sci.* 50:201-210.

Cummings, W. C. 1985. Bryde's whale - *Balaenoptera edeni*. In *Handbook of marine mammals, Vol. 3: The sirenians and baleen whales*, ed. S. H. Ridgway and R. Harrison, 137-154. London: Academic Press.

Cummings, W. C. 1985. Right whales - *Eubalaena glacialis* and *Eubalaena australis*. In *Handbook of marine mammals, Vol. 3: The sirenians and baleen whales*, ed. S. H. Ridgway and R. Harrison, 275-304. London: Academic Press.

Davis, G. E., and M. C. Whiting. 1977. Loggerhead sea turtle nesting in Everglades National Park, Florida, USA. *Herpetologica* 33:18-28.

den Hartog, J. C. 1980. Notes of the food of sea turtles: *Eretmochelys imbricata* (Linnaeus) and *Dermochelys coriacea* (Linnaeus). *Neth. J. Zool.* 30(4):595-610.

Dodd, C. K., Jr. 1982. Nesting of the green turtle, *Chelonia mydas* (L.), in Florida: Historic review and present trends. *Brimleyana* 70:39-54.

Dodd, C. K., Jr. 1988. *Synopsis of the biological data on the loggerhead sea turtle Caretta caretta (Linnaeus 1758)*. Washington, DC: U.S. Fish and Wildlife Service. Biol. Rep. 88(14).

Domning, D. P., and L.-A. C. Hayek. 1986. Interspecific and intraspecific morphological variation in manatees (Sirenia:*Trichechus*). *Mar. Mamm. Sci.* 2(2):87-144.

Forrester, D.J., D.K. Odell, N.P. Thompson, and J.R. White. 1980. Morphometrics, parasites, and chlorinated hydrocarbon residues of pygmy killer whales from Florida. *J. Mammal.* 61(2):356-360.

Fritts, T. H, and R. P. Reynolds. 1981. *Pilot study of the marine mammals, birds, and turtles in OCS areas of the Gulf of Mexico*. FWS/OBS-81/36. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Fritts, T. H., A.B. Irvine, R.D. Jennings, L.A. Collum, W. Hofmann, and M.A. McGhee. 1983. *Turtles, birds, and mammals in the northern Gulf of Mexico and nearby Atlantic waters*. FWS/OBS-82/65. Washington, DC: U.S. Fish and Wildlife Service, Division of Biological Services.

Gambell, R. 1985. Fin whale - *Balaenoptera physalus*. In *Handbook of marine mammals, Vol. 3: The sirenians and baleen whales*, ed. S. H. Ridgway and R. Harrison, 171-192. London: Academic Press.

Gambell, R. 1985. Sei whale - *Balaenoptera borealis*. In *Handbook of marine mammals, Vol. 3: The sirenians and baleen whales*, ed. S. H. Ridgway and R. Harrison, 155-170. London: Academic Press.

Hain, J. H. W., ed. 1990. *Sea turtles and marine mammals of the Gulf of Mexico. Draft proceedings of a workshop held in New Orleans, 1-3 August 1989*.

Handley, C. O., Jr. 1966. A synopsis of the genus *Kogia* (Pygmy sperm whales). In *Whales, dolphins and porpoises*, ed. K. S. Norris, 62-69. Berkeley: Univ. of California Press.

Harris, B. A., W. J. Conley, and J. A. Huff. 1984. *The status of Florida's nesting sea turtle populations from 1979 through 1983*. St. Petersburg: Florida Department of Natural Resources.

Hersh, S. L., and D. K. Odell. 1986. Mass stranding of Fraser's dolphin, *Lagenodelphis hosei*, in the western North Atlantic. *Mar. Mamm. Sci.* 2(1):73-76.

Heyning, J. E. 1989. Cuvier's beaked whale *Ziphius cavirostris* G. Cuvier, 1823. In *Handbook of marine mammals, vol. 4. River dolphins and the larger toothed whales*, ed. S. H. Ridgway and R. Harrison, 289-308. London: Academic Press.

Heyning, J. E., and M. E. Dalheim. 1988. *Orcinus orca. Mammalian Species* 304:1-9.

Hirth, H. F. 1980. Some aspects of the nesting behavior and reproductive biology of sea turtles. *Am. Zool.* 20:507-523.

Hopkins, S. R., and J. J. Richardson, ed. 1984. *Recovery plan for marine turtles*. Washington, DC: National Marine Fisheries Service.

International Whaling Commission. 1977. *Report of the special meeting of the scientific committee on sei and Bryde's whales*. Special Issue No. 1.

International Whaling Commission. 1980. *Sperm whales*. Special Issue No. 2.

Kasuya, T., and H. Marsh. 1984. Life history and reproductive biology of the short-finned pilot whale, *Globicephala macrorhynchus*, off the Pacific coast of Japan. *Int. Whal. Comm., Spec. Issue* 6:259-310.

Katona, S. K., J. A. Beard, P. E. Girton, and F. Wenzel. 1988. Killer whales (*Orcinus orca*) from the Bay of Fundy to the Equator, including the Gulf of Mexico. *Rit Fiskideild.* 11:205-224.

Keller, C. E., and J. K. Adams, ed. 1983. *Proceedings of a workshop on cetaceans and sea turtles in the Gulf of Mexico: Study planning for the effects of outer continental shelf development.* FWS/OBS-83/03. Washington, DC: U.S. Fish and Wildlife Service, Division of Biological Services.

Layne, J. N. 1965. Observations on marine mammals in Florida waters. *Bull. Fla. State Mus. (Biol. Sci.)* 9:131-181.

Leatherwood, S., and R. R. Reeves. 1982. Bottlenose dolphin, *Tursiops truncatus* and other toothed cetaceans. In *Wild mammals of North America - Biology, management, economics*, ed. J. A. Chapman and G. A. Feldhamer, 369-414. Baltimore: The Johns Hopkins Univ. Press.

Leatherwood, S., and R. Reeves. 1983. *The Sierra Club handbook of whales and dolphins.* San Francisco: Sierra Club Books.

Leatherwood, S., and R. Reeves, ed. 1990. *The bottlenose dolphin.* San Diego: Academic Press.

Mead, J. G. 1977. Records of Sei and Bryde's whales from the Atlantic coast of the United States, the Gulf of Mexico, and the Caribbean. In *Report of the Special Meeting of the Scientific Committee on Sei and Bryde's Whales. Rep. Int. Whal. Comm. (Special Issue 1), International Whaling Commission,* 113-116. Cambridge, U.K.

Mead, J. G. 1989. Beaked whales of the genus *Mesoplodon.* In *Handbook of marine mammals, vol. 4. River dolphins and the larger toothed whales*, ed. S. H. Ridgway and R. Harrison, 349-430. London: Academic Press.

Mitchell, E. D., ed. 1975. Review of biology and fisheries for smaller cetaceans. *J. Fish Res. Bd. Can.* 32(7):889-983.

Mitchell, E., and R. R. Reeves. 1988. Records of the killer whale in the western North Atlantic, with emphasis on eastern Canadian waters. *Rit Fiskideild.* 11:161-193.

Moore, J. C. 1953. Distribution of marine mammals to Florida waters. *Am. Midl. Nat.* 49(1):117-158.

Moore, J. C., and F. G. Wood, Jr. 1957. Differences between the beaked whales *Mesoplodon mirus* and *Mesoplodon gervaisi. Am. Mus. Novit.* 1831:1-25.

National Marine Fisheries Service. 1988. *Marine Mammal Protection Act of 1972. Annual report 1987/88.* Washington, DC: U.S. Dept. Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service.

National Marine Fisheries Service. 1989. Draft right whale recovery plan. Unpubl. document.

Odell, D. K. 1982. West Indian manatee, *Trichechus manatus.* In *Wild mammals of North America - Biology, management, economics*, ed. J. A. Chapman and G. A. Feldhamer, 828-837. Baltimore: The Johns Hopkins Univ. Press.

Odell, D. K. In press. A review of the southeastern United States marine mammals stranding network: 1978-1987. In *Proceedings of the Second Marine Mammal Stranding Workshop, Miami, FL, December 1987*, ed. J. E. Reynolds III and D. K. Odell. National Oceanic and Atmospheric Administration, National Marine Fisheries Service.

Odell, D. K., and E. D. Asper. 1986. *A review of pygmy killer whale, Feresa attenuata, strandings in the southeastern United States.* Int. Whal. Comm., Scientific Committee, Document SC/38/SM13.

Odell, D. K., E. D. Asper, J. Baucom, and L. Cornell. 1980. A recurrent mass stranding of the false killer whale, *Pseudorca crassidens*, in Florida. *Fish. Bull.* 78(1):171-177.

Ogren, L., F. Berry, K. Bjorndal, H. Kumpf, R. Mast, G. Medina, H. Reichert, and R. Witham, ed. 1989. *Proceedings of the Second Western Atlantic Turtle Symposium.* NOAA Tech. Mem. NMFS-SEFC-226. Panama City: National Marine Fisheries Service.

Perrin, W. F., and S. Leatherwood. In press. Fraser's dolphin, *Lagenodelphis hosei* Fraser, 1956. In *Handbook of marine mammals, vol. 5*, ed. S. H. Ridgway and R. Harrison. London: Academic Press.

Perrin, W. F., P. B. Best, W. H. Dawbin, K. C. Balcomb, R. Gambell, and G. J. B. Ross. 1973. Rediscovery of Fraser's dolphin, *Lagenodelphis hosei. Nature* 241(5388):345-350.

Perrin, W. F., E. D. Mitchell, J. G. Mead, D. K. Caldwell, and P. J. H. van Bree. 1981. *Stenella clymene*, a rediscovered tropical dolphin of the Atlantic. *J. Mammal.* 62:583-598.

Perrin, W. F., E. D. Mitchell, J. G. Mead, D. K. Caldwell, M. C. Caldwell, P. J. H. van Bree, and W. H. Dawbin. 1987. Revision of the spotted dolphins, *Stenella* spp. *Mar. Mamm. Sci.* 3(2):99-170.

Prescott, J. H., S. D. Kraus, and J. R. Gilbert, ed. 1980. *East coast/Gulf coast cetacean and pinniped workshop, 25-26 September 1979, Boston, MA.* Final Rep. U.S. Mar. Mam. Comm. Contract No. MM1533558-2. Springfield: Nat. Tech. Info. Service.

Pritchard, P. C. H. 1971. *The leatherback or leathery turtle Dermochelys coriacea.* IUCN Monograph No. 1, Morges, Switzerland.

Pritchard, P. C. H. 1979. *Encyclopedia of turtles.* Neptune: TFH Publ., Inc.

Pritchard, P. C. H. 1982. Nesting of the leatherback turtle, *Dermochelys coriacea* in Pacific Mexico, with a new estimate of the world population status. *Copeia* 1982(4):741-747.

Rebel, T. P. 1974. *Sea turtles and the turtle industry of the West Indies, Florida, and the Gulf of Mexico.* Coral Gables: Univ. of Miami Press.

Reeves, R. R., and R. L. Brownell, Jr. 1982. Baleen whales - *Eubalaena glacialis* and allies. In *Wild mammals of North America - Biology, management, economics*, ed. J. A. Chapman and G. A. Feldhamer, 415-444. Baltimore: The Johns Hopkins Univ. Press.

Reynolds, J. E., III, and J. C. Ferguson. 1984. Implications of the presence of manatees (*Trichechus manatus*) near the Dry Tortugas Islands. *Fla. Sci.* 47(3):187-189.

Rice, D. W. 1989. Sperm whale *Physeter macrocephalus* Linnaeus, 1758. In *Handbook of marine mammals, vol. 4. River dolphins and the larger toothed whales*, ed. S. H. Ridgway and R. Harrison, 177-233. London: Academic Press.

Ridgway, S. H., and R. Harrison, ed. 1989. *Handbook of marine mammals. Vol. 4. The beaked whales and river dolphins.* London: Academic Press.

Sadove, S. S., and S. Morreale. 1989. Marine mammal and sea turtle encounters with marine debris in the New York Bight and the Northeast Atlantic. Abstract, *Second International Conference on Marine Debris*, Honolulu, HI, April 1989.

Schmidly, D. J. 1981. *Marine mammals of the southeastern United States coast and the Gulf of Mexico.* FWS/OBS-81/41. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services, Coastal Ecosystems Product.

Scott, G. P., D. M. Burn, L. J. Hansen, and R. E. Owen. 1989. *Estimates of bottlenose dolphin abundance in the Gulf of Mexico from regional aerial surveys.* National Marine Fisheries Service, Southeast Fisheries Center, Miami Laboratory, Coastal Resources Division Contrib. No. CRD-88/89-07.

Sigurjonsson, J., and S. Leatherwood, ed. 1988. North Atlantic killer whales. *Rit Fiskideild.* 11:1-316.

Stewart, B. S., and S. Leatherwood. 1985. Minke whale - *Balaenoptera acutorostrata.* In *Handbook of marine mammals, Vol. 3: The sirenians and baleen whales*, ed. S. H. Ridgway and R. Harrison, 91-136. London: Academic Press.

Townsend, C. H. 1935. The distribution of certain whales as shown by logbook records of American whaleships. *Zoologica* 19:3-50.

True, F. W. 1884. The useful aquatic reptiles and batrachians. In *The fisheries and fishery industries of the United States, Sec. 1, Pt. 2,* 137-162. Washington, DC: U.S. Commercial Fish Fisheries, U.S. Government Printing Office.

van Bree, P. J. H., A. Collet, G. Desportes, E. Hussenot, and J. A. Raga. 1986. Le dauphin de Fraser, *Lagenodelphis hosei* (Cetacea, Odontoceti) espece nouvelle pour le faune d'Europe. *Mammalia* 50(1):58-86.

Van Meter, V. B. 1986. *Florida's sea turtles.* Miami: Florida Power and Light Co.

Van Meter, V. B. 1987. *The West Indian manatee in Florida.* Miami: Florida Power and Light Co.

White, J. R. 1976. A pygmy killer whale found on the east coast of Florida. *Fla. Sci.* 39(1):37-41.

Winn, H. E., and N. E. Reichley. 1985. Humpback whale - *Megaptera novaeangliae. Handbook of marine mammals, Vol. 3: The sirenians and baleen whales*, ed. S. H. Ridgway and R. Harrison, 241-274. London: Academic Press.

Yerger, R. W. 1965. The leatherback turtle on the Gulf coast of Florida. *Copeia* 1965(3):365-366.

Yochem, P. K., and S. Leatherwood. 1985. Blue whale - *Balaenoptera musculus. Handbook of marine mammals, Vol. 3: The sirenians and baleen whales*, ed. S. H. Ridgway and R. Harrison, 193-240. London: Academic Press.

Zieman, J. C. 1982. *The ecology of the seagrasses of South Florida: A community profile.* FWS/OBS-82/85. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

CHAPTER 9
COASTAL AND MARINE BIRDS

Oscar T. Owre

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INTRODUCTION

Birds are an integral part of the ecology of South Florida's coastal and marine habitats. They are also an important element in the aesthetic appeal of South Florida to residents and visitors; to many people, birds are a symbol of the wilderness worthy of our strongest preservation efforts. Accordingly, any new human activities that may threaten South Florida's bird populations or their habitats must be evaluated carefully. In regard to offshore oil and gas activities in the study area, the main concern is oil spills. Major oil spills are rare events, but when they occur, birds are often among the most conspicuous victims.

Birds differ from study area fauna discussed in other chapters in one very important respect: they fly. Therefore, they can move with ease and speed between numerous habitats. Not only can they forage in more than one habitat, but special aspects of their life history are often adapted to different habitats (e.g., foraging, nesting, roosting, and loafing). Habitats may be exploited not only in the diurnal/nocturnal sense, but in the seasonal sense as well. Portions or whole populations of a species may change their geographical range during the year. These facts are important from the standpoint of oil and gas activities, because it means that many birds depend on a variety of uncompromised habitats. Also, it means that birds might encounter oil in more than one place; for example, some species could become contaminated during foraging, even if their nesting habitat were not oiled.

The study area embraces marine and terrestrial ecosystems unique to the U.S. Ecosystems of the study area share with the freshwater wetlands of peninsular Florida a rich diversity of aquatic species. The shoreline assemblages of birds include migrants from the Arctic and Prairie biomes of the continent. Waterfowl from Canada and the northern states spend the winter in habitats of the study area; some of these waterfowl only pause here en route to Caribbean land masses and South America. Hundreds of individuals of many species of hawks migrate into and through the study area, feeding along the way on other bird migrants in the area. Pelagic species (e.g., shearwaters, petrels, and many others) range the open ocean of the study area and approach the coastlines. Nearly 100,000 tropical terns appear seasonally at the Dry Tortugas to nest and rear their young.

Many of the species covered in this chapter are not year-round inhabitants of the study area. But all species discussed, whether permanent residents or temporary visitors

for whatever time periods, obtain food (energy) from the study area's marine or marine-influenced environments. From the energetic standpoint alone, the study area becomes highly important to birds migrating to and from North America and the Neotropics (to the south).

There is not enough space in this chapter to present detailed accounts of *all* bird species that may occur in the study area. Therefore, the chapter presents a more general perspective of South Florida bird populations. Species profiles for selected birds are presented in **Appendix B** and describe the following: (1) occurrence in the study area; (2) seasonality; (3) habitat/natural history; (4) foraging; (5) prey/food; and (6) other comments, including susceptibility of birds to oil.

The chapter begins with a description of geographic areas of special importance to birds: the Ten Thousand Islands, Florida Bay, the Great White Heron and Key West National Wildlife Refuges, and the Dry Tortugas. A second section summarizes information on species in categories of concern, including Endangered and Threatened species as recognized by the U.S. Fish and Wildlife Service (USFWS) and the Florida Game and Fresh Water Fish Commission (FGFWFC). The next three sections present descriptive information on three groups of birds: pelagic birds, coastal birds, and land birds. Within each group, species are considered within the framework of the orders and/or families they represent, which are presented in phylogenetic order (after the American Ornithologists' Union [AOU] *Check-list of North American Birds, 6th edition* [AOU 1983]).

GEOGRAPHIC AREAS OF SPECIAL IMPORTANCE TO BIRDS

The Ten Thousand Islands

From Cape Sable to the northern boundary of the study area, a distance of approximately 130 km (70 nmi), lies a complex maze of channels, mangrove islands, inland bays, and estuaries (**Figure 9.1**; see also **Chapter 2**). Yokel (1983) described this area as a series of "adjacent and interconnected drainage patterns that carry water from the freshwater and cypress sloughs through the fringing mangrove forests into an extensive series of shallow estuaries." South Florida's historian Tebeau (1957) described the Southwest Florida coast as "a region unique in the United States if not in the world." The Ten Thousand Islands are mangrove-covered overwash islands, their symmetries determined by tidal wash, that extend along the coasts' interface with the Gulf.

Estuaries are the "nutrient-rich havens of particular importance to... shallow water euryhaline fishes" (Adams et al. 1973). These estuaries are also the "nurseries" where the pink shrimp, spawned off the Dry Tortugas, develop before returning to their breeding grounds off the Dry Tortugas (Robblee and Tilmant 1987). The euryhaline ichthyofauna is a major food web link between the estuarine primary producers and the commercially or sport-harvested fish. The avifauna is an extension of this link.

Areas in the Ten Thousand Islands (e.g., Chokoloskee Bay, Estero Bay, Indian Key, Marco ABC, and Rogers River Bay) are important to birds for a number of reasons. For cormorants, pelicans, wading birds, and some other species, these areas provide significant nesting rookeries. For waterfowl, Kushlan et al. (1982) reported the largest concentrations of wintering birds in Everglades National Park from these estuaries. For land birds, the mangrove forests along this coast are the habitat of typical land bird assemblages adapted to a marine swamp forest and marine-influenced upland forest. Also, the Gulf-fringing mangroves are the spring landfall of sometimes vast numbers of trans-Gulf migrants coming north from South America.

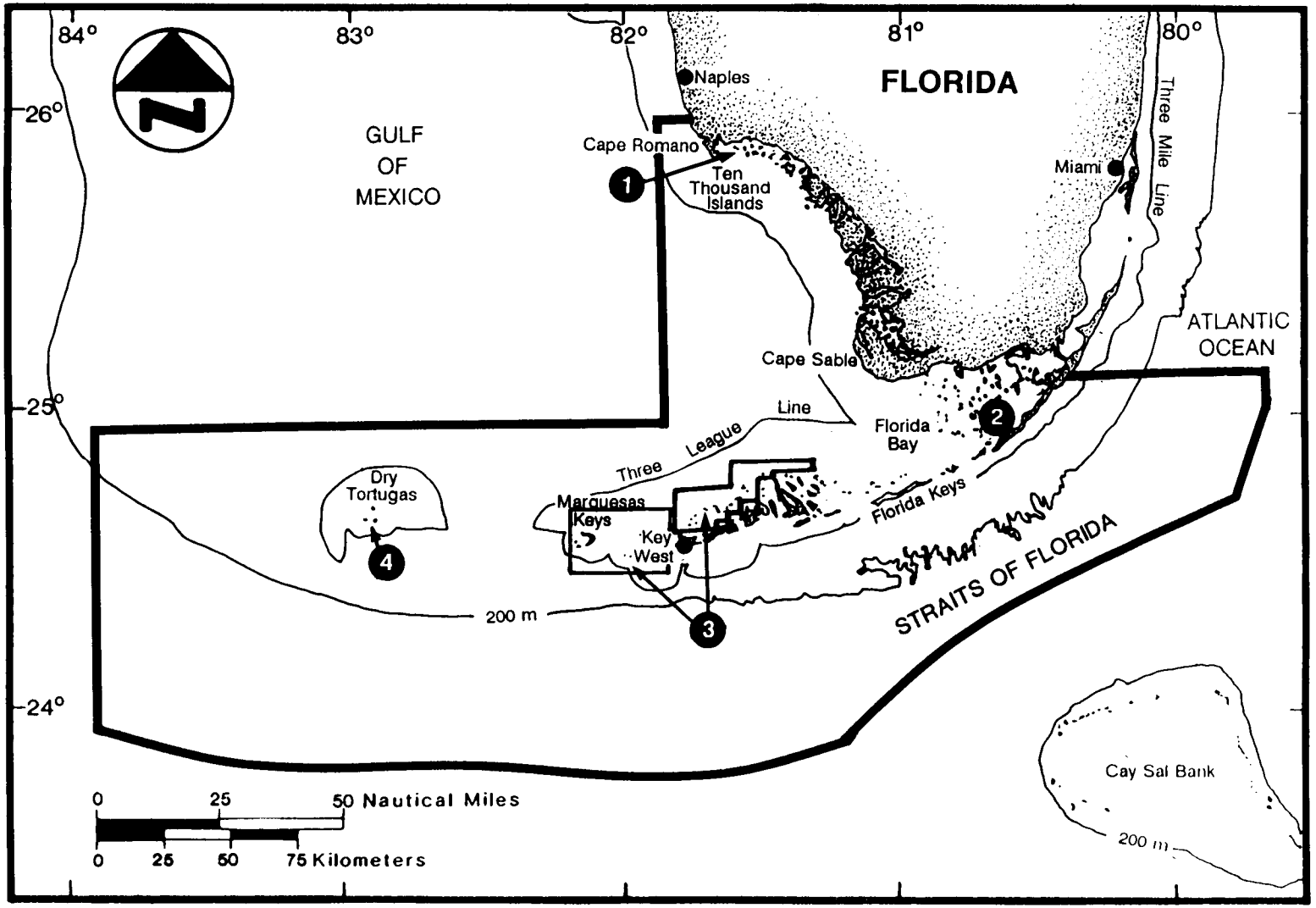

Figure 9.1. Areas of special importance to birds: (1) Ten Thousand Islands, (2) Florida Bay, (3) Great White Heron and Key West National Wildlife Refuges, and (4) Dry Tortugas.

An outstanding feature of the Southwest Florida coast is a series of long, sandy beaches. The beach at Naples, just north of the study area, extends for 12 km (6.5 nmi); the Marco Island beach, for approximately 10 km (5.4 nmi). Sandy-shell beaches rim portions of Cape Romano, and more sandy beaches, sand spits, bars, sand humps, etc. lie to the south. At many points, there are offshore sandy barrier beaches. Anyone who visits these beaches in winter will be impressed with the solid ranks and "clouds" of shorebirds loafing and foraging there. Several species of gulls and terns forage along these beaches and rest upon them. The Cape Romano area is notable for the Big Marco River system of bays and estuaries which have furnished important foraging grounds for pelicans, wading birds, and shorebirds of many species. A wintering concentration of the **American Oystercatcher** (*Haematopus palliatus*), a Species of Special Concern, gathers south of Caxambas Pass in winter. The beaches are one of the few remaining nesting sites of the Threatened **Southeastern Snowy Plover** (*Charadrius alexandrinus tenuirostris*).

Oil floating to these shores could result in a major ecological catastrophe. How long oil might linger in the channels and mangroves of the Southwest Florida coast's estuaries, one could not say. What would the effect be upon the shorebirds foraging along the tidal lines of these beaches? These are very serious considerations that could affect the future of the many avian species that utilize this habitat.

Florida Bay

Florida Bay's area exceeds at least 1,500 km^2 (see **Chapter 2**). It is bordered on the north by the mangroves of the southern rim of the peninsula. From Lake Surprise on the east, the southwestward-oriented Florida Keys form the southern margin. On the west, the bay is open to the Gulf of Mexico (**Figure 9.1**). Exactly where the western margin of the bay should be set is debatable. Some define Florida Bay as comprising those waters within the Everglades National Park Boundary; others, as east of a line stretching from either Key West or the Dry Tortugas to Cape Sable or Cape Romano. Characteristic of the bay is a network of shallow mudbanks (Schomer and Drew 1982). These lie east of a line from western Cape Sable to Sandy Key and then south to Lignumvitae Key. There are geological and ecological reasons for regarding this line as the western margin of Florida Bay (E. Shinn, pers. comm. 1989, U.S. Geological Survey). It is not always clear in the literature, however, what limits are recognized by particular authors. Nor is it always a simple matter to define the activities of volant organisms in terms of two contiguous marine areas. With respect to the subtropical estuary that Florida Bay is, Gusey (1981) characterized it as part of an "estuarine zone that extends from Fort Lauderdale around the tip of Florida inside the Florida Keys to Cape Romano." Again, with respect to volant organisms, "boundaries" within this zone may have little meaning.

Florida Bay's shallow mudbanks partition it into internal basins or "lakes" (Merriam 1987), aquatic vegetation of which affords important habitat for organisms supporting the food web that includes the aquatic birds. Powell (1987) found that wading bird foraging at study sites in different portions of the bay was influenced by "a complex, heterogeneous pattern of water-level fluctuations." These emphasized three cycles: (1) an annual cycle uniform throughout the bay; (2) a daily fluctuation; and (3) a fluctuation dependent upon effects of wind on the bay's shallow waters. The effects of these fluctuations on foraging are discussed in the species profiles (**Appendix B**). Movements of wading birds about, into, and out of the bay are, of course, dependent upon foraging opportunities or food availability. Kushlan (1981) described "seasonal migrations," "radiated dispersals," and "intra-regional movements" of wading birds as adaptations to resource availability. Population movements of these sorts indicate that in the event of oil pollution of the bay, birds present at any given stage of the pollution would be followed by a continuous succession of additional, unaffected numbers. Population movements are discussed in the species profiles. The numerous ecological niches that wading birds occupy in Florida Bay are demonstrated by the broad spectrum

of bird sizes (e.g., bill and leg lengths) and feeding techniques or foraging behaviors, of which Kushlan (1981) described nearly 40.

The role of the red mangrove (*Rhizophora mangle*) in producing detritus that nourishes the food chains supporting Florida Bay's avifauna is well-known (Heald et al. 1974; see also **Chapter 4**). Mangroves are vital to these birds in additional ways. Many wading birds forage in shallow waters below the mangroves. Many roost within the mangroves. In the mangroves of the islands and islets of Florida Bay, wading birds nest, individually or in colonies. The dependence of wading birds, as well as many other aquatic and largely terrestrial birds, upon mangroves is significant. Teas et al. (1989) stressed the fact that "the low-energy sites where mangroves grow are also areas where oil accumulates." These authorities also noted that oil from offshore is carried into mangrove forests by winds and tides, and may persist in mangrove forest soils for years after an oil spill (Teas et al. 1989). In addition to Teas et al. (1989), Odum and Johannes (1975) found that oil can be harmful to mangroves; they cited Gilmore regarding a spill in Guayanilla Harbor, Puerto Rico that "virtually destroyed the mangrove habitat." Additional information about oil spill effects on mangroves is presented in **Chapter 15**. Destruction or degradation of the Florida Bay mangrove habitats would be disruptive to many avian activities.

Florida Bay and its contiguous mangrove areas (Southwest Florida coast and Ten Thousand Islands) present considerations regarding "oil and the avifauna" that have only begun to be addressed (but see Chan 1977). Much of our present information on the subject of birds and oil is derived from northern oceans with arctic, subarctic, and north-temperate avifaunas. King and Sanger (1979) and Clark (1984) discussed oil mortality of murres, puffins, gannets, and other such seabirds with populations of impressive numbers and with breeding colonies spread over wide areas. Hunt (1987), in overview of the question of effects of oil on seabirds, stated "the evidence from northern British Isles and the North Sea is that, for many species, oil-related mortality has not depleted populations" and he continued "calculations of oil-related mortality in relation to natural mortality in seabirds suggests that oil-related deaths represent a small fraction of the natural mortality for most species." In Florida Bay, we are dealing with a subtropical avifauna which is not the same as in the North Atlantic or North Pacific Oceans. Florida Bay's subtropical avifauna is unlike that anywhere else. For example, many wading bird species in Florida Bay are represented by "unique" populations (Powell 1987; see **Appendix B**). The blue morph of the **Great Blue Heron** (*Ardea herodias*) is relatively sedentary and found at the tip of a peninsula along which many species have demonstrable clines (gradations) in characteristics. The individuals of other blue morph populations probably lack "traditions" (fidelity) to this area and their adaptations are not as finely tuned to the bay. Moreover, the population is a relatively small one, probably no more than a very few thousand at best. However, a significant part of the population of the white morph of the Great Blue Heron is found here. In this century, this morph has probably never had more than hundreds or a very few thousand individuals. These are not the immense populations of North Atlantic murres or puffins. Any considerable unnatural mortality beyond that which the population can readily replace would endanger such small populations. The situation is additionally exemplified by the **Reddish Egret** (*Egretta rufescens*) and the **Roseate Spoonbill** (*Ajaia ajaja*). A major portion of the U.S. population of these birds breeds in the bay, and the egret is relatively sedentary. In addition to the wading birds just mentioned, there are birds in the categories of Endangered and Threatened species that winter in Florida Bay, fly through it in migration, or breed around it (see Species in Categories of Concern). Mortality to even *individuals* of these populations should be a cause for real concern.

Florida Bay is an unusual vignette of subtropical climate, water, plants and animals, all interacting in complex ways. Preservation and protection of the Florida Bay ecosystem are critical to South Florida bird populations.

The Great White Heron National Wildlife Refuge and the Key West National Wildlife Refuge

Between Marathon, at the western margin of Florida Bay, and Key West, the offshore keys to the north of the mainline keys constitute the Great White Heron National Wildlife Refuge (**Figure 9.1**). These mangrove-covered keys, distributed over an area more than 70 km (38 nmi) in length, contain nesting sites for the white morph of the Great Blue Heron, other wading birds, and numerous other species (e.g., Double-crested Cormorants, Ospreys, Clapper Rails, Willets, Laughing Gulls, White-crowned Pigeons, Black-whiskered Vireos, Cuban Yellow Warblers, and many others). Nesbitt et al. (1982) identified 14 breeding sites of colonial waterbirds in the approximate area of this refuge. Five of these sites had breeding Brown Pelicans; 11 had Double-crested Cormorants; 8 had Great Blue Herons, white morph; 7 had Great Blue Herons, blue morph; 3 had Great Egrets; and 3 had White Ibis as well as additional species of colonial wading birds. These keys also function as a stopping-place landfall for many spring migrants.

The Key West National Wildlife Refuge embraces the chain of keys extending through 30 km (16 nmi) to the Marquesas Keys. There are about 30 of these keys known as Sand Keys (Davis 1942). These keys harbor many of the nesting species found in the Great White Heron National Refuge. The Marquesas Keys have been a nesting site formerly used (until 1988) by the Magnificent Frigatebird. Tidal flow into the extensive Marquesas lagoon could well draw nearby floating oil into this mangrove-rimmed area. Here, as with the other keys, foraging grounds for many species could be damaged, with serious effects to the avifauna.

The Dry Tortugas

These several islands, the westernmost of the Florida Keys, lie about 110 km (60 nmi) west and slightly north of Key West (**Figure 9.1**). They are in the configuration of an atoll, shaped by winds and tides upon the Tortugas Bank. The central lagoon is almost 16 km (8.6 nmi) in longest diameter, with maximum depths ranging from 9 to 18 m. The Dry Tortugas are composed of coarse-grained, calcareous sand mixed with rubble of coral and other marine organisms. Shorelines are constantly reshaped by wave action; hurricanes and other storms accentuate the reshaping.

More than 125 km (68 nmi) from the Florida mainland (Cape Sable), the Dry Tortugas lie in open waters of the Gulf of Mexico. They rise from the Tortugas Bank near the western edge of the continental shelf. Between the peninsula and the Dry Tortugas, the ocean is shallow (much of it <28 m in depth). The shallow waters, rich in plankton and fish, are frequented by marine and coastal birds. These waters provide a nearby food resource for nesting concentrations of pelagic birds at the Dry Tortugas, especially for tropical terns. To the south, between the islands and Cuba, passes the Florida Current, an oceanic pathway frequented by pelagic birds. To the west lie nutrient-rich waters of the Gulf of Mexico which support the Tortugas shrimp fishery.

Keys of the Dry Tortugas are of two general types: (1) "low" keys with little elevation above the tides, and little or no vegetation; and (2) "high" keys of a more permanent nature, with elevations $\leq$1 m and with considerable vegetation (e.g., Bush, East, Garden, and Loggerhead Keys).

"High" keys support plant cover. Loggerhead Key, about 12 ha in size, has a forest of exotic Australian pines (*Casuarina* sp.) which are important to perching birds that winter there and/or pause in migration. Other trees include sea grapes (*Coccoloba uvifera*) and gumbo-limbo (*Bursera simaruba*), both natives, whose blossoms are

frequented in spring by northward-migrating birds. Bush Key, about 8 ha in size, is the present nesting site of an enormous nesting population of colonial tropical terns. The key is sparsely covered with low bay cedar (*Suriana maritima*); red mangroves are present; and a low plant of saline soil, glasswort (*Salicornia* sp.), grows abundantly, especially in open spaces. About two-thirds of Garden Key's 6 ha is enclosed within the walls of Fort Jefferson. Growing within the central parade ground of the fort are numerous buttonwoods (*Conocarpus erectus*), some large gumbo-limbos, a few geiger-trees (*Cordia sebestena*), and numbers of exotic trees and plants. Outside the fort's walls are large casuarinas, coconut palms (*Cocos nucifer*), numbers of buttonwoods, and other plants. Characteristic of the high islands are numerous, often large, prickly pear cacti (*Opuntia* sp.), sea oats (*Uniola paniculata*), sea lavender (*Tournefortia gnaphalodes*), and some other plants.

Audubon visited the Dry Tortugas in 1832. His paintings and descriptions (Audubon 1831-1839) attracted early attention to an avifauna with tropical, subtropical, temperate and, seasonally, Arctic species, some of these surprisingly abundant. Today, nearly 250 species of birds have been recorded from the islands (Robertson and Mason 1965). Some of these species are now regarded as Endangered or Threatened. Interest and concern for this unusual avifauna are considerable.

An outstanding feature at the Dry Tortugas is the "ternery" where several species of terns nest. Principal among these are two tropical pelagic terns, the **Sooty Tern** (*Sterna fuscata*) and the **Brown Noddy** (*Anous stolidus*), both colonial nesting species. Nowhere in the contiguous U.S. is there another large assemblage of the pan-tropical Sooty Tern. They require a rich supply of food to support their reproductive efforts, and this must lie within energetically convenient flying distances from the colony. Islands confer freedom from terrestrial predators. The island itself must be open enough for their nests. Terns have nested at the Dry Tortugas throughout the recorded history of the area (since 1903). The ternery is now protected from the commercial eggers that formerly carried away tens of thousands of eggs to Cuba and probably other points of consumption. Significant research with the terns has been ongoing for more than 30 years (see e.g., Robertson 1978). Bush Key is a treasury of natural history. Because the terns are uninterrupted in their activities, they have been able to "tell us" much about their biology and biological principles of colonial breeding by pelagic birds.

Apart from marine and coastal species of birds, the Dry Tortugas are noteworthy for trans-Gulf migrations of land birds passing seasonally to and from North America, South America, and the Caribbean. The islands afford stopping (resting) places for large numbers of these, particularly when unfavorable weather overtakes the migrating birds. Thousands of individuals of many species sometimes crowd the surfaces of the land.

Adult Sooty Terns winter offshore in the Gulf of Mexico. Juvenile birds, in their first autumn, perform a trans-Atlantic migration to wintering grounds off the west coast of Africa. At the Dry Tortugas, Sooty Terns begin to gather for breeding shortly before January and numbers increase steadily until early March, when the birds begin landing preparatory to nesting. Currently, the number of breeding pairs is 35,000 to 40,000 and non-breeding birds present bring the total number of individuals to considerably more than this number (W. B. Robertson, pers. comm. 1989, Everglades National Park). By May, egg-laying is well under way and the nesting-area grounds are crowded with walking, courting, and nesting birds. By the end of June, adults and fledged young begin leaving the Dry Tortugas; some remain until late August.

During the nesting period, Sooty Terns on Bush Key (the only island currently nested on) forage widely offshore. Distances of 81 km (44 nmi) are not unusual, and in

bad weather, distances as great as 240 km (130 nmi) have been noted (W. B. Robertson, pers. comm. 1989). The terns follow schools of gamefish and seize the small fish frightened into leaping from the water; they also feed upon flyingfish. Sooty Terns plunge-dive into the water far less than most terns; rather, while flying, they pluck prey from the water. There are important factors for consideration with respect to oil pollution of nesting or foraging areas. The fact that Sooty Terns plunge-dive infrequently during foraging would reduce the danger of oiling their plumage. But this factor is probably not important because their prey (e.g., small fish and squid) plucked from near the surface would presumably be inhibited by oil-covered water. Of importance in the event of oiling of waters near the colony would be whether the birds would shift to oil-free foraging areas. Other areas might not be as productive of the considerable food they require during breeding, and such areas might be too far to be energetically feasible (i.e., the birds might have to fly too far to get food and return).

Sooty Terns nest on the ground in "scrapes" excavated in the sand; nesting space is at a premium in the crowded colony and numbers of scrapes are found very close to the edge of the high-tide mark. Oil washed onto the sandy shore or onto the sand above the high-tide line by winds and waves would be picked up on the feet and plumage of adults as they walk through the colony or on the beach. There is the potential then for oiling of adults as well as eggs, incubating young, and ambulatory young. Young are ambulatory after about 10 days, and move about on the ground until they are 8 to 10 weeks of age, when they begin flying (Robertson 1978); during this period, the likelihood of becoming oiled from polluted beaches would be great. There is another potential for oiling of young. During the warm afternoons, incubating Sooty Terns fly out over the lagoon and dip their belly and breast plumage in the water; then they return to incubate. Dinsmore (1972) suggested that this is a way of reducing egg temperatures. Since this is probably population-wide behavior, oil on the lagoon waters during incubation time (mid to late spring) could result in serious consequences. Fritts et al. (1983) raised the concern that the terns could be affected both directly by oiling and indirectly by mortality of their prey organisms; thus, the food web for the Dry Tortugas population itself could be prejudiced.

Brown Noddies, several hundred to a few thousand, nest annually on Bush Key. These terns build nests in bushes, cacti, and trees. Nests are thus scattered throughout the Sooty Tern colony and elsewhere on Bush Key. When foraging during the breeding season, these terns range less widely over the ocean, as much as one half of the foraging being within the atoll itself (W. B. Robertson, pers. comm. 1989). They also forage eastward as far as Rebecca Shoals. As with the Sooty Terns, this tern seldom plunge-dives, and does not wet its plumage. Noddies gather their nesting material about Bush Key. Oil-encrusted branchlets, seaweed, and pieces of ocean detritus which are utilized in nesting would result in eggs, young, and adults becoming oiled directly from their nests.

Small numbers of other species of terns breed at the Dry Tortugas. The **Least Tern** (*Sterna antillarum*) nests erratically on the ground on both low and high elevation keys (Woolfenden and Robertson 1974). The **Roseate Tern** (*S. dougallii*) has been recorded nesting. Both species are listed as Threatened (FGFWFC 1989; see **Table 9.1**). A few **Black Noddies** (*Anous minutus*) are present each season but have not been discovered nesting. All of these terns forage within the atoll and offshore; they plunge-dive for food. The potential for mortality of adults, eggs, and young from oil in the immediate or offshore environment is obvious.

Of particular interest is the **Magnificent Frigatebird** (*Fregata magnificens*). A population of this large pelecaniform species is usually found around Garden and Bush Keys and elsewhere about the Dry Tortugas. Frigatebirds are kleptoparasites. They

harass terns as they fly to their nests; the food terns carry is then disgorged in flight and seized by the frigatebirds. Frigatebirds are also purported to seize young terns within the ternery. Frigatebirds range widely over the expanse of water from the mainland to the Dry Tortugas, feeding upon flyingfish and frightened baitfish that break the surface. Prior to 1988, the only known nesting site of the Magnificent Frigate within the continental U.S. was at the Marquesas Keys to the east. It no longer nests there. For two years (1988 and 1989), about 25 pairs of frigatebirds have nested on Bush and Loggerhead Keys (W. B. Robertson, pers. comm. 1989). Oil could affect many species of birds, particularly small shorebirds, terns, etc.; those weakened by oiled plumage (e.g., injured, struggling, or weakly flying birds) would be easy prey for frigatebirds, which would become oiled themselves and ingest the oil.

Double-crested Cormorants (*Phalacrocorax auritus*) and **Red-breasted Mergansers** (*Mergus serrator*) are found about the Dry Tortugas; the cormorants, year-round, and the mergansers, in winter. Both of these piscivores pursue their prey underwater. Both species, then, are at a particular peril in oiled waters. The entire population of cormorants at the Dry Tortugas was once eliminated when oil from a stranded freighter (Clark 1984) drifted into the atoll (W. B. Robertson, pers. comm. 1989). Another pelecaniform, the pelagic **Masked Booby** (*Sula dactylatra*), is currently breeding, to the extent of five or six nests on Hospital Key (W. B. Robertson, pers. comm. 1989). Like all boobies, this species plunge-dives and may swim submerged after its prey. Oiled waters would certainly inhibit its activities. This booby nests on isolated keys throughout much of the Caribbean and Gulf of Mexico; but nowhere else along the Atlantic seaboard does it nest in the continental U.S.

Beaches of the Dry Tortugas are thronged both spring and fall with flocks of mixed species of sandpipers (Scolopacidae) and plovers (Charadriidae) passing to and from wintering areas to the south and nesting grounds in the North American prairies, tundra, etc. Fewer than about 500 of these, chiefly **Black-bellied Plovers** (*Pluvialis squatarola*), **Willets** (*Catoptrophorus semipalmatus*), **Ruddy Turnstones** (*Arenaria interpres*), and **Sanderlings** (*Calidris alba*), winter at the atoll. These species forage on small invertebrates along the beach and the beach/water interface (littoral zone), and thus are intolerant of oil-soaked sand.

The Dry Tortugas figure prominently in the natural history of a number of raptors (birds of prey) in their twice-yearly migrations. The Arctic subspecies of the **Peregrine Falcon** (*Falco peregrinus tundrius*), a Threatened (USFWS) and Endangered (FGFWFC) species, uses the Dry Tortugas as a stopping/foraging place between its South/Central American/Gulf Coast wintering areas and the eastern North American/Greenland nesting grounds. Between the 15th of September and end of October, as many as 300 of these falcons pause here, chiefly on Loggerhead Key (T. Smylie, pers. comm. 1989, USFWS, Albuquerque, NM). How critical an area it is to these birds is emphasized by Smylie's sightings of as many as 30 of the falcons at a time on this island of approximately 12 ha. The falcons perch atop the Key's tall casuarina trees and, when sighting passerines and other birds migrating past, launch forth, stoop at the prey and either knock or force it into the water, then circle and pick up the bird. Plumages of predator and prey alike could become oiled. Three hundred of these falcons are, no doubt, an important component of the subspecies' entire population.

Numbers of **Merlins** (*Falco columbarius*) pause at the Dry Tortugas in migration. Merlins, just as the larger falcons, feed on migrating small birds. Hundreds of **Sharp-shinned Hawks** (*Accipiter striatus*) accompany the migration of their prey, small passerines, to the Dry Tortugas; these too could be subject to oiling. Other raptors (e.g., **Northern Harriers** [*Circus cyaneus*] and **Short-eared Owls** [*Asio flammeus*]) reach the Dry Tortugas in migration.

In summary, it seems clear that oil pollution affecting the Dry Tortugas could, depending upon the time of spill, jeopardize breeding populations, wintering populations, and migrating populations of a spectrum of species with both marine and terrestrial affinities. Individual birds raised here come back to nest. Mass mortality of terns at Bush Key would be a tragedy. An oil spill here would also severely affect ongoing studies critical to an understanding of the biology of the terns.
W. B. Robertson, Jr. and his associates have been gathering data on the Dry Tortugas terneries for more than 25 years, and trends now beginning to be perceived could be obscured. Equally serious would be the possible effects upon the many raptors present in fall, winter, and spring. The reproductive efforts of these birds which nest hundreds or thousands of kilometers away could be affected. Moreover, substances with unknown effects could be introduced into both marine and terrestrial food webs.

SPECIES IN CATEGORIES OF CONCERN

Section 7 of the Endangered Species Act of 1973 stipulates that Federal agencies "plan their projects so as not to disrupt Endangered and Threatened species or their Critical Habitats" (see Reed and Drabelle 1984). The spirit of this provision should dictate close consideration to any leasing of government lands for oil and gas exploration and development offshore South Florida.

Inventory of the Endangered, Threatened, and otherwise designated Species of Concern within the study area will focus attention not only on individual species and groups of species but will identify Critical Habitats as well. Four species found within the study area are currently designated Endangered ("in danger of extinction throughout all or significant part of its range") (see **Table 9.1**):

- Arctic Peregrine Falcon
- Bald Eagle
- Cape Sable Seaside Sparrow
- Wood Stork

A Threatened Species is one "likely to become an Endangered species over a significant part of its range within the foreseeable future" (Reed and Drabelle 1984). Species designated Threatened within the study area are as follows (see **Table 9.1**):

- Arctic Peregrine Falcon
- Bald Eagle
- Florida Sandhill Crane
- Least Tern
- Piping Plover
- Roseate Tern
- Southeastern Snowy Plover
- Southeastern American Kestrel
- White-crowned Pigeon

Species of Special Concern are so designated by the states in which they occur. This designation calls attention to unfavorable regional factors or regional reductions in numbers of a species. They may also be species whose status in Florida has a potential impact on Endangered or Threatened populations or on other species outside the State. Species of Special Concern found within the study area are as follows (see **Table 9.1**):

Table 9.1. Birds within the study area designated under official categories of concern (From: Florida Game and Fresh Water Fish Commission 1989).

Species	Category of Concern*		
	Federal†	State§	CITES¶
American Oystercatcher (*Haematopus palliatus*)	--	SSC	--
American Swallow-tailed Kite (*Elanoides forficatus*)	UR5	--	--
Arctic Peregrine Falcon (*Falco peregrinus tundrius*)	T	E	Schedule I
Bald Eagle (*Haliaeetus leucocephalus*)	E	T	Schedule I
Brown Pelican (*Pelecanus occidentalis*)	--	SSC	--
Burrowing Owl (*Athene cunicularia*)	--	SSC	--
Cape Sable Seaside Sparrow (*Ammodramus maritimus mirabilis*)	E	E	--
Eastern American Kestrel (*Falco sparverius sparverius*)	--	--	Schedule II
Florida Sandhill Crane (*Grus canadensis pratensis*)	--	T	Schedule II
Least Tern (*Sterna antillarum*)	--	T	--
Limpkin** (*Aramus guarauna*)	--	SSC	--
Little Blue Heron (*Egretta caerulea*)	--	SSC	--
Mangrove Clapper Rail (*Rallus longirostris insularum*)	UR2	--	--
Merlin (*Falco columbarius*)	--	--	Schedule II
Northern Harrier (*Circus cyaneus*)	--	--	Schedule II
Osprey (*Pandion haliaetus*)	--	SSC (Monroe County)	Schedule II

Table 9.1. (Continued).

Species	Category of Concern*		
	Federal‡	State§	CITES¶
Piping Plover (*Charadrius melodus*)	T	T	--
Reddish Egret (*Egretta rufescens*)	UR2	SSC	--
Roseate Spoonbill (*Ajaia ajaja*)	--	SSC	--
Roseate Tern (*Sterna dougallii*)	T	T	--
Snowy Egret (*Egretta thula*)	--	SSC	--
Southeastern Snowy Plover (*Charadrius alexandrinus tenuirostris*)	UR2	T	--
Southeastern American Kestrel (*Falco sparverius paulus*)	UR2	T	Schedule II
Swainson's Hawk (*Buteo swainsoni*)	UR5	--	--
Tricolored Heron (*Egretta tricolor*)	--	SSC	--
White-crowned Pigeon (*Columba leucocephala*)	UR2	T	--
Wood Stork (*Mycteria americana*)	E	E	--

* E = Endangered; T = Threatened; SSC = Species of Special Concern; UR2 = Under review for listing, but substantial evidence of biological vulnerability and/or threat is lacking; UR5 = Still formally under review for listing, but no longer considered for listing because recent information indicates species is more widespread or abundant than previously believed; Schedule I = Species with greatest threat of extinction; Schedule II = Species under threat.
‡ Federal = U.S. Fish and Wildlife Service.
§ State = Florida Game and Fresh Water Fish Commission.
¶ CITES = Convention on International Trade in Endangered Species.
**The Limpkin is a bird of freshwater habitats and enters the study area infrequently.

- American Oystercatcher
- Brown Pelican
- Burrowing Owl
- Little Blue Heron
- Osprey (Monroe County)
- Reddish Egret
- Roseate Spoonbill
- Snowy Egret
- Tricolored Heron

Species designated "Under Review" are under consideration for listing as Endangered or Threatened by the USFWS. Categories UR1 through UR5 pertain to the amount of information the Agency has in terms of evidence for listing, UR1 being the strongest evidence. The Secretary of the Interior then has one year in which to decide if sufficient evidence is at hand to warrant listing. Decisions are published in the Federal Register; concerned parties have 60 days in which to comment. Currently designated as "Under Review" are the following species occurring within the study area (see **Table 9.1**):

- American Swallow-tailed Kite
- Mangrove Clapper Rail
- Reddish Egret
- Southeastern Snowy Plover
- Southeastern American Kestrel
- Swainson's Hawk
- White-crowned Pigeon

Finally, the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) maintains listings of species considered Threatened by being objects of international trade. (The Endangered Species Act applies only to persons under jurisdiction of the U.S. Persons of all the signing nations of this Convention, nearly 90 nations, are under the jurisdiction of the signatory nations). "Schedule" designations *I* and *II* are based on the magnitude of threat to the species, with *I* representing the greatest threat. CITES has the following current listings of species found within the study area (see **Table 9.1**):

- Arctic Peregrine Falcon
- Bald Eagle
- Eastern American Kestrel
- Florida Sandhill Crane
- Merlin
- Northern Harrier
- Osprey
- Southeastern American Kestrel

The summary of species listed in **Table 9.1** is a long list--27 species (the two Kestrel subspecies are counted here as separate entities). Few continental areas of comparable size harbor as many species in precarious statuses. What, then, of the habitat(s) these birds occupy? Initially, one can say that all are parts of a single ecosystem, the fauna of which constitutes a single food web with innumerable interconnecting food chains. The birds' places of activity as well as the activities themselves can be correlated with what we may identify as very generalized habitats. Habitats are points of first consideration in management for the species in Categories of Concern.

Six species of long-legged wading birds (Little Blue Heron, Reddish Egret, Roseate Spoonbill, Snowy Egret, Tricolored Heron, and Wood Stork) forage in wadable parts of the study area: Florida Bay, the Southwest Florida coast, and the Florida Keys to the Marquesas and the Dry Tortugas; and variably, in brackish and even freshwater wetlands inland of the marine ecosystem. Because their major food is fish as well as other aquatic organisms of these areas, these "wadable areas" can be called, albeit from a simplistic standpoint, Critical Habitat.

If one considers the prey fish of the study area, one can add to the above six species five additional fish-eating birds: the Brown Pelican, Osprey, Bald Eagle, and Roseate and Least Terns. Eleven species in Categories of Concern, then, forage in Florida Bay and its adjoining inshore waters. We can thus call the expanded aquatic area a Critical Habitat and the fish therein can be identified as a Critical Resource for avian species in Categories of Concern.

The mangrove forests also stand out as Critical Habitat, not only from trophically furnishing the starting point of food webs, but also as affording nesting and foraging opportunities for many species. In addition to the wading birds and the other fish-eating birds mentioned above (excluding the terns) at least six species that are in large part dependent upon terrestrial resources may be added to the list of mangrove-oriented birds of concern. These are the American Swallow-tailed Kite, Arctic Peregrine Falcon, Eastern American Kestrel, Mangrove Clapper Rail, Merlin, and White-crowned Pigeon. Over half of these birds are fish-foragers, and about half are diurnal birds of prey. The Osprey and Bald Eagle have been listed as occupying an expanded aquatic habitat and exploiting the same critical resource, the fish of the Areas of Concern. In the event of extensive avian mortality from whatever sources of pollution, sickened and dying birds probably would be harvested by birds of prey, including the Bald Eagle.

Another category involves five species which have as primary habitat the sandy beaches and exposed tidal flats. The American Oystercatcher, Least Tern, Piping Plover, Roseate Tern, and Southeastern Snowy Plover are birds of this category.

Other species on the list of those in Categories of Concern include three specialized species with restricted habitats. The Burrowing Owl is an entirely terrestrial predator, foraging over open ground and requiring a depth of soil for its burrows. The Florida Sandhill Crane nests at the interface of freshwater and mangroves along the Southwest Florida coast. The Cape Sable Seaside Sparrow now breeds only at inland freshwater habitats.

Clearly, if the species in Categories of Concern are to be successfully managed, the following areas must be maintained as viable ecosystems: (1) the waters of Florida Bay and contiguous inshore waters, as well as brackish and critical freshwater habitats immediately inland; (2) the coastal and inshore waters along the Florida Keys to and including Key West, the Marquesas Keys, and the waters around the Dry Tortugas; (3) the waters of the Southwest Florida coast and the Ten Thousand Islands and contiguous waters; (4) sandy beaches and tidal flats, and (5) the mangrove forests. These ecosystems constitute much of the study area.

INTRODUCTION TO THE BIRD GROUPS

Profiles of bird species are presented in **Appendix B**. Someone seeking information about birds occurring within the study area should find within the individual profiles the basic information about each species. References included in the profiles can be consulted for additional information. Here, general information is presented by taxa within three categories: pelagic birds, coastal birds, and land birds. Pelagic birds are species that, except when nesting, pass their lives at sea, usually far from land. The coastal bird group includes a variety of taxa that are associated with coastal marine or brackish water habitats. Land birds are species that, typically, are not modified for aquatic life. They live largely or entirely on land. Those that enter the study area are more or less influenced by the nearby, often surrounding, marine ecosystems.

A brief discussion of terminology is in order. The following designations are widely used in describing seasonal occurrence (see e.g., Wallace and Mahan 1975):

- **Permanent Resident**. Species present the year-round within a given locality. Only some part of a species' population may be permanently resident; that part usually breeds. Another portion of the population may be migratory. Example: many heron species have a permanently resident population within an area and breed there. Their numbers are augmented in winter by migrants from elsewhere but these migrants do not breed in the area.

- **Winter Resident**. Present only in winter. Such birds usually do not breed in the area.

- **Summer Resident**. Species that are present only in summer; this is usually their reproductive season.[1] This may not be the case with pelagic birds that breed in the Southern Hemisphere in their summer and spend their "winter" in the Northern Hemisphere summer.

- **Migratory Visitor**. Species present only while passing through the study area in fall (about August to October) or spring (about March to May) or during both these periods.

- **Casual Visitor**. Individuals or numbers of individuals of a species present only occasionally and often with irregularity.

- **Accidental Visitor**. Occurrence unexpected and not predictable. Caution must be used in applying this designation. With species whose ranges are poorly known, as is the case with many pelagic birds, this designation may not accurately portray the situation. Also, with respect to changing ranges, first records may be called Accidental Visitors; later, as birds become more common, this designation will change.

[1] "Breeding season" is a term seasonally well-defined in the Temperate Zone. It is not as well defined in the subtropics and tropics, where some species may breed over considerable periods of time; often such extended breeding seasons will have one or more "pulses" of major breeding. Some water birds of the study area, e.g., the **Double-crested Cormorant** (*Phalacrocorax auritus*), can be found breeding in any month, but there are times when major numbers breed.

South Florida birds can also be grouped by their ecological habitats. Three major zones are recognized:

- Intertidal Zone. The area lying between mean low and high tides.
- Inshore Zone. From the lower edge of the intertidal zone to about 8 km (4.3 nmi) from shore.
- Offshore Zone. From about 8 km (4.3 nmi) offshore to the continental shelf edge (200 m depth). Found here are species that (1) return to land at night; and (2) enter the area from the pelagic zone and, except when breeding, are independent of land.

When considering oil pollution, it is important to know how birds forage. Species foraging while swimming submerged are at greatest risk in oiled waters as are those that plunge from the surface to depth. Those that swim at the surface while foraging or while resting/sleeping are at considerable risk. Less risk should be faced by those species that pluck or skim from the surface. Wading birds can be vulnerable to oiling. Those walking/running along oiled beaches and tidal flats face great risk. Foraging birds in oiled marshes are at risk. Scavengers ingesting oiled carcasses may suffer sublethal aftereffects or be killed. Reactions of birds at initial encounter with oil are not known. It is also unknown whether nocturnal foragers such as night-herons and skimmers face greater risk than diurnal foragers. The following is a summary of the many ways in which birds may be adapted to forage (see Ashmole 1971).

- Forage underwater (submerged) while swimming.
- Plunge from air into water--shallow plunging or deep plunging which is usually terminated by swimming.
- Forage while swimming on surface--reach to bottom for food; filter material from water with bill; scoop or pick food from surface.
- Forage from surface while in flight--skim surface with bill; pluck from surface.
- Forage while wading or walking.
- Forage in mangroves (not from intertidal zone waters)--forage from bark or twigs; glean from leaves; "flycatch" within and above canopy; forage above canopy while in rapid flight.
- Forage as predators or robbers (kleptoparasites) of other birds.
- Scavenge upon dead animals, refuse, etc.

PELAGIC BIRDS

Pelagic birds, except when nesting, pass their lives at sea, usually far from land. Foraging methods are an important consideration with respect to oil-contaminated water.

Except for the large numbers of Sooty and Noddy Terns and the few Masked Boobies which also breed at the Dry Tortugas, none of the species of pelagic birds occurring in the study area breed in this area; a very few species breed nearby. While most occur well offshore and can be expected to occur only in the outer fringes of the study area, some do enter inshore waters and even the larger bays. The seasonal distribution patterns of many pelagic birds are not well known (this is emphatically the

case for the offshore zone within the study area). Few of the species can be found in the study area year-round. Large populations of many species move northward and/or southward during migration, offshore of the peninsula; the seasonal "pulses" of these movements are imperfectly known. A few species wander into the area with regularity or irregularity. Some have been scarcely recorded in Florida's offshore waters but may occur with greater regularity than is realized.

In varying degree, depending upon their habits, pelagic birds are particularly vulnerable to oil in their environment. Mortality from oil has been scarcely appreciated because "a large fraction of the total mortality may remain unmeasured" (Ford et al. 1987). Carcasses are not necessarily washed ashore; many may sink or are eaten, as may the live birds themselves when flight becomes impeded. To what extent do the various species respond to floating oil? We seem to know no more about this now than Bourne (1970), who wrote that birds "most often become polluted because, when encountering oil, they simply fail to recognize it as a hazard."

Of particular concern are those pelagic birds (e.g., phalaropes) that gather on the sea to forage. Also of concern are the migrating pelagic birds, numbers of which may pass offshore. If the birds shift their foraging areas and/or aquatic resting areas before becoming oiled, mortality will be mitigated. Another consideration is ingested oil, about which little is known. Birds ingest oil from preening and eating oiled prey. Controlled experiments, albeit with birds of very different taxa from pelagic ones, give results that are difficult to interpret (Clark 1984), but there exists the potential for reproduction impediments. Among breeding pelagic birds, compromised reproduction may occur in birds breeding not only nearby, but those breeding thousands of kilometers away, and in the Southern as well as the Northern Hemispheres. Consequently, unknown factors may be introduced into food webs of nearby and remote ecosystems.

With respect to the occurrences of pelagic species, one cannot exactly separate the Straits of Florida and the Eastern Gulf of Mexico Planning Areas. By and large, these species will appear mainly in the areas offshore of the 100-m depth contour. Some of the species orient themselves with respect to the warm Florida Current/Gulf Stream and, inshore from it, the cooler southward flowing countercurrent. But birds may move inshore of this, and those species that find their way around the peninsula to the Gulf of Mexico, may well pass not far offshore of the Florida Keys, and even penetrate Florida Bay and pass close enough to Cape Romano to be seen from the shore. Indication of where individual species can be expected to occur, if known, will be given in the species profiles (**Appendix B**).

Species of pelagic birds known to occur in the study area are listed in **Table 9.2.** Discussions of major taxa under this heading are presented below.

Shearwaters, Petrels, and Storm-Petrels (Order Procellariiformes)

The Procellariiformes are "the most marine of all living birds" (Palmer 1962). All of the nearly 100 species are pelagic. All must come to land to nest, usually on predator-free oceanic or offshore islands, headlands, or mountain cliffs. Breeding is usually colonial. One egg is laid either in a crevice or burrow, on bare ground, or, uncommonly on a mound of scraped-up dirt. Breeding birds, depending upon the species, forage at varying distances offshore. Prey items include organisms found at or near the surface (e.g., fish, cephalopods, and crustaceans). After breeding, adults and fledged young of many species disperse, often over vast areas; some have pronounced seasonal migrations, with some being inter-hemispheric. Dispersers and migrants move to take advantage of favorable foraging within water masses of the oceans.

Table 9.2. Pelagic birds known to occur in the study area.

Species	Seasonality*	Primary Habitat(s)	Foraging	Category of Concern
SHEARWATERS AND PETRELS				
Audubon's Shearwater (*Puffinus lherminieri*)	CV All months	Offshore and less commonly inshore	Feeds at surface and shallow-dives from flight	--
Cory's Shearwater (*Calonectris diomedea*)	MV	Offshore and less commonly inshore	Swimming at surface; seldom dives	--
Greater Shearwater (*Puffinus gravis*)	MV May-Jun	Offshore and less commonly inshore	Plunge-dives; pursues prey underwater	--
Manx Shearwater (*Puffinus puffinus*)	AV Winter	Offshore and less commonly inshore	Plunge-dives; pursues prey underwater	--
Sooty Shearwater (*Puffinus griseus*)	MV May-Jun	Offshore and less commonly inshore	Plunge-dives; pursues prey underwater	--
Black-capped Petrel (*Pterodroma hasitata*)	CV Any month	Offshore and less commonly inshore	Seizes from surface while in flight	--
Bulwer's Petrel (*Bulweria bulwerii*)	AV May	Offshore and less commonly inshore	Seizes from surface while in flight	--
STORM-PETRELS				
Band-rumped Storm-Petrel (*Oceanodroma castro*)	CV	Offshore and less commonly inshore	While fluttering above surface	--
Leach's Storm-Petrel (*Oceanodroma leucorhoa*)	CV Oct-May	Offshore and less commonly inshore	While fluttering above surface	--
Wilson's Storm-Petrel (*Oceanites oceanicus*)	MV May-Oct	Offshore and less commonly inshore	While fluttering above surface	--
TROPICBIRDS				
Red-billed Tropicbird (*Phaethon aethereus*)	AV Any month	Offshore	Plunge-dives; ingests prey before surfacing or while swimming	--
White-tailed Tropicbird (*Phaethon lepturus*)	CV Any month	Offshore and inshore	Plunge-dives; ingests prey before surfacing or while swimming	--

Table 9.2. (Continued).

Species	Seasonality*	Primary Habitat(s)	Foraging	Category of Concern
BOOBIES AND GANNETS				
Brown Booby (*Sula leucogaster*)	PR	Offshore, frequently inshore	Plunge-dives; pursues prey underwater	--
Masked Booby (*Sula dactylatra*)	PR	Offshore, inshore, breeds Dry Tortugas	Plunge-dives; pursues prey underwater	--
Red-footed Booby (*Sula sula*)	CV Any month	Offshore, less commonly inshore	Plunge-dives; pursues prey underwater	--
Northern Gannet (*Sula bassanus*)	WR Dec-May	Offshore, frequently inshore	Plunge-dives; pursues prey underwater	--
PHALAROPES				
Red Phalarope (*Phalaropus fulicaria*)	MV Oct-Mar	Offshore, less commonly inshore, infrequently littoral	While swimming	--
Red-necked Phalarope (*Phalaropus lobatus*)	MV Oct-Mar	Offshore, less commonly inshore, infrequently littoral	While swimming	--
Wilson's Phalarope (*Phalaropus tricolor*)	MV Aug-Oct and Mar-Jun	Freshwater and marine littoral	Walking; swimming picks from surface; probes in mud	--
JAEGERS AND SKUAS				
Long-tailed Jaeger (*Stercorarius longicaudus*)	CV Nov-May	Offshore, rarely inshore	Picks from surface; kleptoparasite of seabirds	--
Parasitic Jaeger (*Stercorarius parasiticus*)	MV Nov-May	Offshore, inshore	Picks from surface; kleptoparasite of seabirds	--
Pomarine Jaeger (*Stercorarius pomarinus*)	MV Nov-May	Offshore, inshore	Picks from surface; kleptoparasite of seabirds	--
Great Skua (*Catharacta skua*)	CV Any month	Offshore, rarely inshore	Picks from surface; kleptoparasite of seabirds	--

Table 9.2. (Continued).

Species	Seasonality*	Primary Habitat(s)	Foraging	Category of Concern
GULLS				
Black-legged Kittiwake (*Rissa tridactyla*)	CV Oct-Apr	Offshore, inshore	Dips-to-surface; plunge-dives	--
Sabine's Gull (*Xema sabini*)	CV Aug	Offshore, inshore	Picks from water while in flight	--
TERNS				
Arctic Tern (*Sterna paradisaea*)	MV	Offshore, less frequently inshore	Plunge-dives	--
Black Noddy (*Anous minutus*)	SR, not known to breed	In summer, Dry Tortugas	While in flight, plucks prey from surface; seldom plunge-dives	--
Bridled Tern (*Sterna anaethetus*)	CV	Offshore, less frequently inshore	Hovers and dips	--
Brown Noddy (*Anous stolidus*)	SR Jan-Aug	Nests Dry Tortugas offshore, inshore	While in flight, plucks prey from surface	--
Sooty Tern (*Sterna fuscata*)	SR Breeds: Jan-Aug	Nests Dry Tortugas inshore, offshore	While in flight, plucks prey from surface; seldom plunge-dives	--

* AV = Accidental Visitor; CV = Casual Visitor; MV = Migratory Visitor; PR = Permanent Resident; SR = Summer Resident; WR = Winter Resident.

All these species are predators, most being at or near the apices of food webs. They are long-lived, a characteristic typical of pelagic birds. However, because of their low reproductive rate (i.e., one young per year), any out-of-the-ordinary mortality could have serious effects on population densities and colony integrities. Species of two families of this order are represented in the study area.

Shearwaters and Petrels (Family Procellariidae)

This is the largest family of procellariids, containing more than 50 species of medium to large-sized (22 to 72 cm in length) shearwaters and petrels. The birds forage over the open oceans of the world, flapping and gliding close to the water. Many snatch prey from the water's surface; some dive and pursue prey underwater; and a few follow whale pods and ships for prey that may be exposed, and for refuse and offal. Individuals, as well as small and large-sized flocks, rest on the water. Foraging in some is crepuscular and nocturnal; in others, it is diurnal. Seven species of shearwaters and petrels reach the study area (**Table 9.2**).

Audubon's Shearwater (*Puffinus lherminieri*) frequents tropical seas including those (Atlantic and Gulf of Mexico) bordering peninsular Florida. The birds nest near Florida--Cay Sal Bank, islands offshore Cuba, the Bahamas, etc., from November to July. Cay Sal Bank is 250 km (135 nmi) from the Dry Tortugas and only about 80 km (43 nmi) from the edge of the study area opposite Marathon. After breeding, populations disperse widely, but no pronounced migrations have been discerned. Birds seen regularly off Florida are those foraging from nearby breeding concentrations as well as the post-breeding dispersants. Foraging is by day and night, singly or in small groups. The birds spend much time on the water and dive freely. They tend to concentrate at upwellings or strong currents (Palmer 1962). This is the most abundant species of procellariid offshore Florida year-round; individuals enter Florida Bay and other large inshore waters. They are vulnerable to oil in the environment, and any considerable mortality would probably be reflected in the numbers present at neighboring breeding areas (e.g., Cay Sal Bank).

Cory's Shearwater (*Calonectris diomedea*) nests on islands of the eastern Atlantic and the Mediterranean. From late summer through fall, numbers frequent the western Atlantic and the Gulf of Mexico, thus appearing offshore along coasts of the entire Florida peninsula. The species occurs from the outer limits of both the Straits of Florida and Eastern Gulf of Mexico Planning Areas to points close offshore. The late Al Pflueger encountered "flocks" offshore from Miami south along Key Largo during fall (A. Pfleuger, pers. comm. 1961); he collected specimens "four miles east of Tavernier, Key Largo" on 6 October 1961 (two of these specimens are in the University of Miami reference collections). Actual abundance of Cory's Shearwater offshore South Florida is not known, but it is apparently common at times. Haney and McGillivary (1985) found these shearwaters to be the dominant seabird off the Atlantic coast of northern Florida in July and October. These birds were congregated at thermal fronts of the Gulf Stream where vertical transport episodically brings organisms to the surface. This shearwater, a largely nocturnal forager, picks up squid and small fish from the surface (Watson 1966). Cory's Shearwater dives less than other shearwaters. It is seasonally and locally vulnerable to oil in offshore areas. Clapp et al. (1982) reported that in pelagic areas, the species may roost on the water in "immense rafts." Certainly such flocks would be extremely vulnerable to floating oil. Fritts et al. (1983) considered potential effects of coastal or offshore oil spills for this species as severe.

Two inter-hemispheric migrants, the **Greater Shearwater** (*Puffinus gravis*) and the **Sooty Shearwater** (*P. griseus*), occur offshore Florida. The former nests at the Tristan da Cunha Islands (South Atlantic); the latter, on subantarctic islands. Migrating

northward along the Gulf Stream, Sooty Shearwaters begin reaching Florida in May, the greatest numbers arriving before early summer. Since the Gulf Stream passes very close offshore the study area, species following it may pass close offshore Florida Bay. Buckley (1973) at Cape Hatteras, North Carolina, at a point where the Gulf Stream may pass "as close as 8 to 10 miles offshore" witnessed during about nine hours spread over four days in May and June, between 2,000 to 3,000 each of Greater and Sooty Shearwaters and more than 5,000 Cory's Shearwaters pass by. University of Miami reference collections contain a specimen found dead off Windley Key on 21 May 1975. Greater Shearwaters are now known to occur regularly in the Gulf of Mexico (Clapp et al. 1982). The Greater Shearwater is thought to occur in the larger numbers. Numbers of the Sooty, however, must be considerable at certain times; farther north than Florida "thousands of dead Sooty Shearwaters have been recorded washing ashore after storms" (Terres 1980). Both species are predominantly nocturnal in foraging; both dive and pursue prey underwater; and both are vulnerable to offshore oil. Large numbers could be affected by floating masses of oil.

Two additional procellariids reach Florida's offshore waters, possibly as Casual Visitors. The **Manx (Common) Shearwater** (*Puffinus puffinus*), after breeding on islands offshore northern U.S. and Europe, moves southward in the Atlantic as far as Florida. Excellent swimmers and divers, they rest on the surface in flocks. The **Black-capped Petrel** (*Pterodroma hasitata*), a species much reduced in numbers (Greenway 1967), breeds on mountaintops (e.g., in Cuba and Hispaniola), frequenting the Caribbean and adjacent waters of the Atlantic, particularly the warm sides of subtropical convergences. Lee (1986) reported the petrel relatively common all year off North Carolina. Breeding season of this petrel is from April to August (Greenway 1967). According to Haney (1986b), the species is most abundant between 32° and 33°N where wide meanderings of the Gulf Stream produce maximum numbers of upwellings.

The first North American record (hypothetical in absence of a photograph or a specimen) for **Bulwer's Petrel** (*Bulweria bulwerii*) is from Rebecca Passage between the Marquesas Keys and the Dry Tortugas (Taylor 1972). In the Atlantic, this species breeds on Cape Verde and Madeira Islands; it migrates regularly southwest toward the New World continents. At present, the species can only be listed as an Accidental Visitor.

Storm-Petrels (Family Hydrobatidae)

Storm-Petrels are the smallest of the Procellariiformes, some being scarcely larger than swallows. Pelagic, the species all range far over the oceans. They breed on islands or isolated land masses, nesting in burrows or crevices. After breeding, the species either disperse from the nesting areas or perform inter-hemispheric migrations ranging far over the oceans. Storm-Petrels typically feed by hovering over the water, using "foot-pattering" and "wing-lift" to keep aloft. Birds often settle on the sea in groups, numbering in the hundreds. Small fish, crustaceans, and planktonic organisms of many kinds as well as refuse on the ocean surface, are taken. According to Haney (1986a,b), Storm-Petrels occur off the coast of the southeastern U.S. when Gulf-Stream eddies are numerous; these eddies cause upwellings which contain abundances of food. Few Storm-Petrels occur from June to September when eddies are less frequent.

Three species of Storm-Petrels can be encountered in offshore Florida waters (**Table 9.2**). **Leach's Storm-Petrel** (*Oceanodroma leucorhoa*) breeds from Massachusetts northeastward to Iceland, Scotland, and Norway. After breeding, the species ranges at sea to the West Indies, the Caribbean, offshore Florida, and the Gulf of Mexico. It occurs casually within offshore portions of the study area. **Wilson's Storm-Petrel** (*Oceanites oceanicus*) breeds circumpolarly on subantarctic islands. Post-breeding

migrations northward bring populations to tropical/subtropical ocean masses. From May to July, less commonly into fall, occurrence can be expected within the study area, not only offshore but occasionally within Biscayne Bay, for example (Howell 1932). The **Band-rumped Storm-Petrel** (*Oceanodroma castro*) has been recorded from Key West, Upper Matecumbe Key, and offshore Florida localities from the Gulf of Mexico to the Atlantic and outside the study area (Sykes et al. 1984). This tropical Storm-Petrel may be more common in Florida waters than is now realized.

Tropicbirds (Order Pelecaniformes, Family Phaethontidae)

Two species of Tropicbirds may occur in the study area (**Table 9.2**). The **White-tailed Tropicbird** (*Phaethon lepturus*) breeds in the Bahamas, Greater and Lesser Antilles, and offshore islands in the Gulf of Mexico. After breeding, the birds wander singly or in pairs long distances from land. This is a Casual Visitor to the southern part of the Florida peninsula. Breeding birds from elsewhere or non-breeding birds may occur anywhere within the study area. They dive from heights (up to 16-m high) for fish, cephalopods, and crustacea which they swallow while submerged or at the surface. Nesting situations are variable: burrows, caves, crevices, under bushes, etc. Dangers of serious mortality from oiling are mitigated because the species is casual in occurrence and solitary in habits. The **Red-billed Tropicbird** (*P. aethereus*) has been recorded offshore Florida (Clapp et al. 1982).

Boobies and Gannets (Order Pelecaniformes, Family Sulidae)

This family consists of boobies, which are entirely tropical in distribution, and gannets, which breed on inaccessible cliffs above cold, temperate zone waters. Three boobies and one gannet occur in the study area (**Table 9.2**). All sulids dive for their prey (e.g., fishes, cephalopods, and crustaceans), from heights of 16 m and more; they pursue prey for some distance underwater. Flocks of the birds, particularly gannets, often gather where foraging is good.

Three tropical sulids occur in the study area: the **Masked Booby** (*Sula dactylatra*), the **Brown Booby** (*S. leucogaster*), and the **Red-footed Booby** (*S. sula*). The first is currently nesting at the Dry Tortugas (see Clapp and Robertson 1986 and the Dry Tortugas section in this chapter). The Brown Booby formerly bred at the Dry Tortugas (Howell 1932). The Red-footed Booby breeds in the Greater and Lesser Antilles and is a vagrant to both coasts of Florida (Watson 1966) where it can occur in the study area. These boobies currently breed at many points around the Caribbean and occur casually within the study area. Brown Boobies frequently can be seen at the lighthouse marker at Rebecca Shoals. All dive for food and rest on the water. All represent a unique element of the tropical avifauna, the tropical marine pelagic species.

Western Atlantic populations of the **Northern Gannet** (*Sula bassanus*) breed in large "gannetries" (hundreds of individuals) in eastern Canada. These birds begin southward migration in September, with the "general 'target area' apparently being off Florida" (Nelson 1978), which is reached in December; by January, juveniles are the first to arrive in the Gulf of Mexico, later followed by other age groups. By February, all age groups are in the Gulf of Mexico, and adults are beginning to migrate northward again. Immatures leave in March. University of Miami reference collections contain Broward County specimens from April and May. Being sulids of cold water masses, these migrating gannets tend to move in the cool countercurrent inshore of the Gulf Stream. The writer has watched small flocks (as many as 25 to 30 birds) moving offshore in both the Atlantic and Gulf of Mexico. Because gannets and boobies plunge to depth to pursue prey underwater, and because they rest on the surface, they are among those species most vulnerable to oiled waters.

Phalaropes (Order Charadriiformes, Family Scolopacidae: Phalaropodinae)

Phalaropes are robin-sized, sandpiper-like birds when ashore, but are swimming birds when offshore and in the open sea. Three species occur in the study area (**Table 9.2**).

All three species, **Wilson's Phalarope** (*Phalaropus tricolor*), the **Red-necked Phalarope** (*P. lobatus*), and the **Red Phalarope** (*P. fulicaria*), breed in the Northern Hemisphere. The latter two breed circumpolarly at high latitudes. Wilson's Phalarope, which is essentially freshwater at all seasons, breeds on North American prairies and migrates south through the Florida peninsula. All three species spend winter in the Southern Hemisphere. Both the Red-necked and Red Phalaropes are found littorally, as well as offshore; University of Miami reference collections contain specimens of both species from marine littoral situations, and contain several specimens of the Red-necked Phalarope taken in October "offshore." The late A. Pflueger (pers. comm. 1958 to 1961, Miami marine fish taxidermist and naturalist) frequently encountered flocks on the water close to, but offshore the southern peninsula and the Keys. From satellite-derived hydrographic data, Haney (1986b) correlated *Phalaropus* distribution in fall and winter (October to March) with the Gulf Stream's mid-shelf front, where the birds congregated within a 50 km (27 nmi) cross-shelf width. Phalaropes feed on plankton at upwellings, feeding while swimming. The birds stir up the macroplankton by swimming in circles. Phalaropes associate in flocks while pelagic. They are extremely vulnerable to oil offshore.

Jaegers and Skuas (Order Charadriiformes, Family Laridae: Stercorariinae)

Skuas and jaegars are gull-sized birds and breed circumpolarly. After breeding, these Northern Hemisphere birds migrate south, offshore, along the continental coastlines. The winter is spent in subtropical/tropical oceans, the birds ranging from offshore the coastlines to far at sea (see **Table 9.2**).

The **Pomarine Jaegar** (*Stercorarius pomarinus*), **Parasitic Jaegar** (*S. parasiticus*), and **Long-tailed Jaegar** (*S. longicaudus*) occur irregularly during winter months within the study area, from the outer boundaries to the bays, estuaries, and nearshore waters. The Long-tailed Jaegar is pelagic to a greater degree than other jaegars and is seen less often along coastlines. The **Great Skua** (*Catharacta skua*) is regarded as a Casual Visitor to Florida offshore waters (AOU 1983). Williams (1965) listed earlier occurrences of jaegers in the Gulf of Mexico, including several records from the study area. Because jaegars appear infrequently, and then in small numbers, there is little concern for them regarding oil in the study area.

Gulls (Order Charadriiformes, Family Laridae:Larinae)

Gulls are mainly birds of inshore coastal waters and continental freshwater habitats. Few are active offshore beyond the continental shelf. A very few species are pelagic. Two of these are casual or of erratic occurrence offshore Florida from autumn to spring (**Table 9.2**).

The **Black-legged Kittiwake** (*Rissa tridactyla*) breeds circumpolarly. In the Atlantic, it nests as far south as Newfoundland and Spain. After breeding, these birds disperse over the Atlantic to waters mainly between 60° and 40°N, but small numbers are found to about 25°N; vagrants move erratically even farther south (Cramp et al. 1983). Kittiwakes are seen, unpredictably, offshore the Florida peninsula. The University of

Miami reference collections contain a specimen from St. Lucie County; this bird has oil on its belly and lower breast. Main prey of the Black-legged Kittiwake are fishes and invertebrates. Foraging behaviors include "dipping to surface," "aerial pattering," and "surface-plunging" to about 1 m depth. Because few kittiwakes are likely to occur in the study area, this species (and also the Sabine's Gull mentioned below) raises little concern regarding oil in the study area.

Sabine's Gull (*Xema sabini*) has breeding populations in the Atlantic, in Greenland, and in Canada. These populations migrate in August to regions of cool upwellings off southern Africa. Return migration begins March through April. During absence from the breeding grounds, individuals occur casually offshore eastern Florida (Barber and Johnson 1976). The species has occurred at the Dry Tortugas (Collie 1978).

Terns (Order Charadriiformes, Family Laridae:Sterninae)

The majority of the 43 species of terns inhabit the seacoasts and/or the interior marshes and lakes of the continents. Migrations, often over wide expanses of ocean, are performed by species nesting at high latitudes. A few terns are pelagic (**Table 9.2**).

The **Bridled Tern** (*Sterna anaethetus*) is Pan-Tropical. It nests abundantly on islands of the Caribbean (e.g., the Bahamas; the Lesser and Greater Antilles). It does not nest in Florida. In the Bahamas, eggs are laid from mid-April to late June. The birds may be seen regularly in offshore Florida waters, and undoubtedly enter the study area throughout the year. University of Miami reference collections include specimens from the following months: two from Ft. Lauderdale, 31 December and 23 April; two from Dade County, 10 September and 10 August; one from 8 km (4.3 nmi) offshore south Key Largo, 2 September; and one from the Dry Tortugas, Garden Key, 12 May. Buhrman and Hopkins (1978) commented on "surprising" numbers seen on 10 trips offshore Pasco and Pinellas Counties in the Gulf. Wayne Hoffman (pers. comm. 1989, Research Department, National Audubon Society) regards the Bridled Tern as one of the commonest seabirds during spring and summer at the edge of the Gulf Stream along the southern end of the Florida peninsula. According to Clapp et al. (1983), this tern is "considerably more abundant ... off the Atlantic coast and in the Gulf of Mexico than was previously thought." Presumably, Bridled Terns offshore Florida are breeding birds foraging from nearby nesting sites (e.g., Cay Sal Banks), as well as post-breeding individuals. According to Cramp et al. (1985), they are active both night and day.

The **Brown Noddy** (*Anous stolidus*), the **Black Noddy** (*A. minutus*), and the **Sooty Tern** (*Sterna fuscata*), all pelagic species, have been discussed in the Dry Tortugas section. The **Arctic Tern** (*S. paradisaea*), "mostly pelagic" (AOU 1983), breeds on far northern continental situations and winters as far south as the Antarctic; small numbers, at least, are found in migration off the Florida peninsula, apparently mainly in spring (Clapp et al. 1983). **Black Terns** (*Chlidonias niger*) (which breed inland), along with other terns which breed inland as well as along coastal areas, migrate to southern wintering areas and return, often in numbers. Buhrman and Hopkins (1978) encountered more than 1,000 Black Terns in the open Gulf offshore the peninsula of Florida on 25 September 1976, these obviously migrating birds. The extent to which migrants may land on water is not known, but migrants feed there (e.g., the Black Tern plucks fish from the surface). Some potential for oiling of numbers of migrating birds exists.

COASTAL BIRDS

The "coastal birds" grouping includes species that are associated with coastal marine or brackish habitats. This is a heterogenous group that includes wading birds, shorebirds, waterfowl, birds of prey, etc. Species known to occur in the study area are listed in **Table 9.3.**

Loons (Order Gaviiformes, Family Gaviidae)

Loons are foot-propelled divers, so highly modified for submerged foraging that they have lost the ability to walk. Except when flying, or tending nests on floating islets, their lives are spent in water. They breed circumpolarly on Arctic and Boreal Zone freshwater lakes. Highly migratory, they spend winter along coastlines of the northern continents.

Three species of loons are known from the study area (**Table 9.3**): the **Arctic Loon** (*Gavia arctica*), the **Common Loon** (*G. immer*), and the **Red-throated Loon** (*G. stellata*). The Common Loon is included in the species profiles (**Appendix B**).

Grebes (Order Podicipediformes, Family Podicipedidae)

Grebes are highly specialized aquatic birds. Like loons, they cannot walk on land. When not flying or atop their floating nests, they are confined to water. While the species have freshwater breeding habitats, northern grebes migrate; and in winter, some seek out coastal estuaries, sheltered bays, and inlets. They seldom frequent exposed coasts or offshore waters.

Six species of grebes are recorded in the study area (**Table 9.3**): **Eared Grebe** (*Podiceps nigricollis*), **Horned Grebe** (*Podiceps auritus*), **Least Grebe** (*Tachybaptus dominicus*), **Pied-billed Grebe** (*Podilymbus podiceps*), **Red-necked Grebe** (*Podiceps grisegena*), and **Western Grebe** (*Aechmophorus occidentalis*). The Pied-billed Grebe has both migratory and breeding populations in South Florida; the other five are migrants. The Pied-billed Grebe and the Horned Grebe are included in the species profiles (**Appendix B**). Grebes are highly vulnerable to floating oil.

Pelicans and Allies (Order Pelecaniformes)

This order embraces six families, all adapted for marine/aquatic living. Of the two families previously discussed under **Pelagic Birds**, one, the Phaethontidae (Tropicbirds), is exclusively pelagic; the other, the Sulidae (Boobies and Gannets), is adapted for somewhat different degrees of oceanic existence. Species of the remaining four families occupy prominent niches in the non-pelagic portions of the study area (see **Table 9.3**).

Pelicans (Family Pelecanidae)

Two species of pelicans are present in the study area: the **American White Pelican** (*Pelecanus erythrorhynchos*) and the **Brown Pelican** (*P. occidentalis*). The latter is a Species of Special Concern (FGFWFC 1989). Pelicans are the largest of the pelecaniform birds, with the American White Pelican having a wingspread of nearly 3 m. Pelicans either scoop fish from the water, while swimming (American White Pelican), or "plunge-dive" for fish (Brown Pelican).

Table 9.3. Coastal birds known to occur within the study area.

Species	Seasonality*	Primary Habitat(s)	Foraging	Category of Concern†
LOONS				
Arctic Loon (*Gavia arctica*)	AV	Inshore, offshore, estuaries, bays	Swims submerged	--
Common Loon (*Gavia immer*)	WR	Inshore, offshore, estuaries, bays	Swims submerged	--
Red-throated Loon (*Gavia stellata*)	CV Oct-May	Inshore, offshore, estuaries, bays	Swims submerged	--
GREBES				
Eared Grebe (*Podiceps nigricollis*)	CV Winter	Freshwater, coastal	Swims submerged	--
Horned Grebe (*Podiceps auritus*)	WR Oct-Apr	Coastal, inshore	Swims submerged	--
Least Grebe (*Tachybaptus dominicus*)	AV Any month	Freshwater	Swims submerged	--
Pied-billed Grebe (*Podilymbus podiceps*)	PR, WR WR Sep-May	Freshwater, mangrove shorelines	Swims submerged	--
Red-necked Grebe (*Podiceps grisegena*)	CV Winter	Freshwater, coastal	Swims submerged	--
Western Grebe (*Aechmophorus occidentalis*)	AV Winter	Freshwater, coastal	Swims submerged	--
PELICANS AND ALLIES				
Pelicans				
American White Pelican (*Pelecanus erythrorhynchos*)	WR Oct-May	Principally mangrove shorelines, Cape Sable area, less frequently freshwater areas	Swims, scoops fish	--

Table 9.3. (Continued).

Species	Seasonality*	Primary Habitat(s)	Foraging	Category of Concern†
Brown Pelican (*Pelecanus occidentalis*)	PR, WR Breeds: Mar-Apr	Protected coastal waters	Plunge-dives	SSC-FGFWFC
Cormorants				
Double-crested Cormorant (*Phalacrocorax auritus*)	PR, WR Breeds: Oct-Mar	Protected coastal waters, less frequently freshwater	Swims submerged	--
Great Cormorant (*Phalacrocorax carbo*)	CV Winter	Protected coastal waters	Swims submerged	--
Anhingas				
Anhinga (*Anhinga anhinga*)	PR, WR Breeds: Dec-Apr	Largely freshwater, quiet mangrove waters; nests in mangroves	Swims submerged	--
Frigatebirds				
Magnificent Frigatebird (*Fregata magnificens*)	PR Breeds: Irregularly	Inshore, offshore; nests on mangroves and bushes of Keys	While in flight, picks from surface; kleptoparasite of seabirds	--
HERONS AND ALLIES				
Bitterns, Egrets, and Herons				
Least Bittern (*Ixobrychus exilis*)	SR, WR Present all months Breeds:Jun-Jul	Dense, emergent aquatic vegetation, marine or freshwater	Within dense vegetation varied foraging methods	--
Cattle Egret (*Bubulcus ibis*)	PR, MV	Nests in colonial, water-bird rookeries in mangroves	On uplands	--

Table 9.3. (Continued).

Species	Seasonality*	Primary Habitat(s)	Foraging	Category of Concern†
Great Egret (*Casmerodius albus*)	PR, WR, MV Breeds: Dec-Apr	All wadable wetlands and dry prairie	Stand and wait, walk slowly, etc.	--
Little Blue Heron (*Egretta caerulea*)	PR, WR, MV Breeds: Dec-Jun	Shallow wetlands, particularly freshwater	Many different foraging behaviors	SSC - FGFWFC
Reddish Egret (*Egretta rufescens*)	PR Breeds:Nov-Feb	Brackish marshes, shallow coastal habitats	Much varied: walks, runs, uses wings, etc.	SSC - FGFWFC UR2 - USFWS
Snowy Egret (*Egretta thula*)	PR, WR, MV WRs, MVs Oct-May Breeds:Mar-Aug	Wadable wetlands, coastal and freshwater	Much varied: walking, flying, etc.	SSC - FGFWFC
Tricolored Heron (*Egretta tricolor*)	PR, WR, MV Breeds: Feb-Jul	Shallow, quiet coastal areas	Many different foraging behaviors	SSC - FGFWFC
Black-crowned Night-Heron (*Nycticorax nycticorax*)	PR, WR, MV Breeds: Dec-May	Estuaries and islets, coastal and freshwater	Standing, walking slowly, etc.; diurnal, nocturnal	--
Great Blue Heron Blue color morph (*Ardea herodias*)	PR, WR WRs Oct-Apr Breeds: Sep-Feb	Coastal, estuarine, freshwater	Stand and wait, walk slowly; diurnal, nocturnal	--
Great Blue Heron White color morph (*Ardea herodias*)	PR; Breeds: Sep-Feb nocturnal	Coastal, estuarine	Stand and wait, walk slowly; diurnal,	--
Green-backed Heron (*Butorides striatus*)	PR, MV MVs Oct-Apr Breeds: Mar-May	Forested water margins, coastal and freshwater	Standing in crouched position, walking slowly, etc.	--
Yellow-crowned Night-Heron (*Nycticorax violaceus*)	PR, WR, MV Breeds:Mar-Jul	Mangrove shorelines, mudflats	Standing while looking for prey; walks slowly; diurnal, nocturnal	--

Table 9.3. (Continued).

Species	Seasonality*	Primary Habitat(s)	Foraging	Category of Concern†
Ibises and Spoonbills				
Glossy Ibis (*Plegadis falcinellus*)	PR Opportunistic breeder	Freshwater, less frequently marine wetlands	Visual and tactile; picks and probes; shallow water and damp, dry ground	--
White Ibis (*Eudocimus albus*)	PR Opportunistic breeder	Marine and freshwater wetlands, beaches, and pastures	Visual and tactile; picks and probes; shallow water and damp, dry ground	--
Roseate Spoonbill (*Ajaia ajaja*)	PR, WR, SR Breeds: Nov-Apr	Coastal mangroves, swamps, and freshwater wetlands	Tactile; shallow water; spatulate bill moved side to side	SSC - FGFWFC
Storks				
Wood Stork (*Mycteria americana*)	PR Breeds: Nov-Apr	Freshwater and marine wetlands	Tactile; shallow water; bill contacts prey and snaps shut	E - FGFWFC E - USFWS
WATERFOWL				
American Wigeon (*Anas americana*)	WR, MV Oct-May	Freshwater areas, coastal	Dabbling	--
Blue-winged Teal (*Anas discors*)	WR, MV Aug-May	Freshwater areas, coastal	Dabbling	--
Lesser Scaup (*Aythya affinis*)	WR, MV Oct-May	Marine waters, more often than freshwater	Diving	--
Mottled Duck (*Anas fulvigula*)	PR Breeds:Feb-Jul	Freshwater and coastal wetlands	Dabbling	--
Northern Pintail (*Anas acuta*)	WR, MV Oct-Mar	Freshwater areas, coastal	Dabbling	--

Table 9.3. (Continued).

Species	Seasonality*	Primary Habitat(s)	Foraging	Category of Concern†
Red-breasted Merganser (*Mergus serrator*)	WR, MV Oct-May	Coastal and inshore waters	Diving	--
Ring-necked Duck (*Aythya collaris*)	WR, MV Oct-Apr	Freshwater areas, more often than coastal	Diving	--
VULTURES, HAWKS, AND FALCONS				
Vultures				
Black Vulture (*Coragyps atratus*)	PR	Ubiquitous - mainland; rare in Keys	From flight; visual clues	--
Turkey Vulture (*Cathartes aura*)	PR, WR	Ubiquitous, land and littoral areas	From flight; visual and olfactory clues	--
Kites, Eagles, Hawks, and Ospreys				
American Swallow-tailed Kite (*Elanoides forficatus*)	SR	Countryside with mixed forest growth - mangroves, etc.	While in flight	UR5 - USFWS
Bald Eagle (*Haliaeetus leucocephalus*)	PR, WR	Seacoasts, lakes, and rivers with tall trees nearby for nesting	Plunging and picking from water surface; picking from land; scavenges	T - FGFWFC E - USFWS CITES I
Broad-winged Hawk (*Buteo platypterus*)	WR, MV Oct-May	Dense wooded areas including mangroves; tropical hammocks	Watches from tree or perches, and launches forth at prey	--
Northern Harrier (*Circus cyaneus*)	WR, MV	Marshes, coastal prairies, and shorelines	While in flight, at 7 to 10 m height, drops on prey	CITES II
Red-shouldered Hawk (*Buteo lineatus*)	PR Breeds:Jan-Mar	Forested freshwater and marine wetlands; mangroves, tropical hammocks	Watches from perches in forest or open areas, and launches forth at prey	--

Table 9.3. (Continued).

Species	Seasonality*	Primary Habitat(s)	Foraging	Category of Concern†
Sharp-shinned Hawk (*Accipiter striatus*)	WR, MV	Landscapes with forests (mangroves), scattered growth	Prey pursued in flight, often through woodland	--
Short-tailed Hawk (*Buteo brachyurus*)	PR, WR WR Oct-Feb Breeds:Mar-Jun	Forested perimeters of Florida Bay and inland	Slow-soaring and plunges to canopy or ground	--
Swainson's Hawk (*Buteo swainsoni*)	WR Nov-Mar	Open areas, agricultural land	Perches on ground or poles; forages on ground animals	UR5 - USFWS
Osprey (*Pandion haliaetus*)	PR, MV	Freshwater and marine areas with trees/utility poles, etc. for nests	Plunge-dives	SSC - FGFWFC CITES II
Falcons				
Arctic Peregrine Falcon (*Falco peregrinus tundrius*)	WR, MV Sep-May	Seacoasts, estuaries, urban areas; requires dead trees, poles, etc. for lookouts	Still-hunts; launches forth at prey, then stoops at it; picks up from ground or water	E - FGFWFC T - USFWS CITES I
Eastern American Kestrel (*Falco sparverius sparverius*)	WR Oct-Apr	Fringes of growth, open landscape with scattered growth, pineland	Sights prey from perch or hovering; dives on prey	CITES II
Merlin (*Falco columbarius*)	WR, MV Sep-May	Seacoasts, edges of woodlands, mangroves	Sights prey from perch or hovering; dives on prey or pursues in flight	CITES II
Southeastern American Kestrel (*Falco sparverius paulus*)	PR, WR PR extirpated? WR if present?	Fringes of growth, open landscape with scattered growth, pineland	Sights prey from perch or hovering; dives on prey	T - FGFWFC UR2 - USFWS CITES II

Table 9.3. (Continued).

Species	Seasonality*	Primary Habitat(s)	Foraging	Category of Concern†
CRANES AND ALLIES				
Coots and Rails				
American Coot (*Fulica americana*)	WR Oct-Apr	Brackish bays, estuaries, mangrove lakes, and freshwater areas	Dabbles; dives and picks up while walking	--
Black Rail (*Laterallus jamaicensis*)	SR?, WR? No data	Salt marshes, freshwater marshes	Seldom observed	--
Florida Clapper Rail (*Rallus longirostris scottii*)	PR, Breeds: Mar-Jun	Coastal swamps of mainland	Walks and runs; picks and probes	--
King Rail (*Rallus elegans*)	PR, WR, MV Breeds: Feb-Jun	Freshwater wetlands, salinities below 3.7 ppt	Walks and runs; picks and probes	--
Mangrove Clapper Rail (*Rallus longirostris insularum*)	PR, Breeds: Mar-Jun	Coastal swamps of Florida Keys	Walks and runs; picks and probes	UR2 - USFWS
Sora (*Porzana carolina*)	WR, MV	Freshwater and brackish marshes	Walks, wades, picks up	--
Virginia Rail (*Rallus limicola*)	WR, MV Uncommon	Freshwater wetlands; rare in brackish and coastal marshes	Walks and runs; picks and probes; seldom observed	--
Yellow Rail (*Coturnicops noveboracensis*)	WR, MV Uncommon?	Freshwater and brackish marshes	Walks; picks and probes; seldom observed	--
Cranes				
Florida Sandhill Crane (*Grus canadensis pratensis*)	PR	Freshwater marshes near interface with coastal mangroves	While walking, picks and probes	T - FGFWFC CITES II

Table 9.3. (Continued).

Species	Seasonality*	Primary Habitat(s)	Foraging	Category of Concern†
SHOREBIRDS				
Plovers				
Black-bellied Plover (*Pluvialis squatarola*)	WR, MV Oct-May Some summer	Surf line, mud flats, and salt marshes	Runs, pauses, pecks	--
Killdeer (*Charadrius vociferus*)	PR, WR, MV WRs Oct-Mar Breeds: Mar-May	Coastal and freshwater shorelines, mudflats, filled areas, levees, vacant lots, etc.	Short runs; head bobbing; picks up; diurnal, nocturnal	--
Piping Plover (*Charadrius melodus*)	WR, MV Jul-May	Coastal, sandy beaches	Runs, pauses, stares, picks up; small groups; diurnal, nocturnal	T - FGFWFC T - USFWS
Semipalmated Plover (*Charadrius semipalmatus*)	WR, MV Jul-May	Sandy beaches, tidal mudflats	Runs rapidly; intertidal zone; picks exposed food; in flocks	--
Southeastern Snowy Plover (*Charadrius alexandrinus tenuirostris*)	PR Breeds:Mar-May	Sandy beaches, upper and tidal	Runs, pauses, pecks	T - FGFWFC UR2 - USFWS
Wilson's Plover (*Charadrius wilsonia*)	SR, WR Breeds:Apr-Jul	Sandy beaches, tidal mudflats	Crouch, run, pick up; diurnal, nocturnal	--
Oystercatchers				
American Oystercatcher (*Haematopus palliatus*)	WR, PR No breeding in study area	Sand beaches near mollusc beds	Special techniques for opening clams and oysters	SSC - FGFWFC
Avocets and Stilts				
American Avocet (*Recurvirostra americana*)	WR Sep-May	Saline mudflats	In water or on mud; versatile: pecks, plunges, scythes, filters, etc.	--
Black-necked Stilt (*Himantopus mexicanus*)	SR, rare WR SRs Feb-Oct Breeds:Apr-Jun	Freshwater, marine wetlands	Wades, walks; jabs, plunges head and neck	--

Table 9.3. (Continued).

Species	Seasonality*	Primary Habitat(s)	Foraging	Category of Concern†
Sandpipers and Allies				
Dunlin (*Calidris alpina*)	WR, MV Sep-May	Sandy beaches, tidal flats	Probes and snatches	--
Greater Yellowlegs (*Tringa melanoleuca*)	WR, MV	Shallow water, tidal flats and mud flats; coastal; also inland	Wades; picks, swings bill, ploughs water, etc.; runs after fish	--
Least Sandpiper (*Calidris minutilla*)	WR, MV Jul-May	Sandy beaches, tidal flats	Snatches from surface; probes soft substrates; moves and pauses	--
Marbled Godwit (*Limosa fedoa*)	WR, MV WRs Jul-May	Coastal, estuaries, oyster reefs	Probes in mud and oyster reefs	--
Red Knot (*Calidris canutus*)	WR, MV Sep-Nov, Mar-May A few winter	Intertidal zone	In flocks, closely-spaced; steps, multiple probes, etc.	--
Ruddy Turnstone (*Arenaria interpres*)	WR, MV Aug-Apr	Upper and lower beaches, especially tidal zone	Uses bill to overturn pebbles, shells, and debris; digs, pulls apart seaweed on tide line	--
Sanderling (*Calidris alba*)	WR, MV WRs Aug-May	Sandy beaches	Small flocks	--
Semipalmated Sandpiper (*Calidris pusilla*)	WR, MV WRs Jul-Apr	Beaches, intertidal zone, and mudflats	Snatches and probes	--
Short-billed Dowitcher (*Limnodromus griseus*)	WR, MV Jul-May	Sheltered coastal beaches, mudflats, marshes, flooded fields, and shallow brackish water	Probes rapidly; bill about 50 to 70 mm; in mud, sand, drift-zone seaweeds; wades	--
Western Sandpiper (*Calidris mauri*)	WR, MV Aug-May	Sandy beaches, tidal flats	Snatches from surface; probes soft substrates; moves and pauses	--

Table 9.3. (Continued).

Species	Seasonality*	Primary Habitat(s)	Foraging	Category of Concern†
Willet (*Catoptrophorus semipalmatus*)	PR?, WR, SR, MV Breeds:Apr-Jun	Sandy beaches, mudflats, and salt marshes	Probes, snatches while wading/walking	--
Gulls (non-pelagic)				
Bonaparte's Gull (*Larus philadelphia*)	WRs Oct-May Uncommon Sep-May	Littoral, inshore, inland	Plunges; swims and walks	--
Herring Gull (*Larus argentatus*)	WR, MV Oct-May	Littoral, inshore, inland	Dips to surface; plunges to shallow depths; swims and walks for prey; kleptoparasite flies in pursuit	--
Laughing Gull (*Larus atricilla*)	SR, WR, MV, PR? Year-round Breeds:Mar-Aug	Littoral, inshore, inland	Hovers; dips to surface; swims and walks for prey	--
Ring-billed Gull (*Larus delawarensis*)	WR, MV Oct-Apr Some all year	Littoral, inshore, inland	Hovers; dips to surface; swims and walks for prey	--
Terns				
Arctic Tern (*Sterna paradisaea*)	MV Irregular	Offshore; inshore	Hovers and plunge-dives	--
Black Tern (*Chlidonias niger*)	MV	Offshore; inshore; inland	Hovers, plunge-dives, dips to surface, and pursues insects	--
Bridled Tern (*Sterna anaethetus*)	CV	Offshore, less frequently inshore	Hovers and dips to surface	--
Caspian Tern (*Sterna caspia*)	WR, MV	Coastlines, estuaries, and freshwater wetlands	Dips to surface, plunge-dives, swims and dives; kleptoparasite	--
Common Tern (*Sterna hirundo*)	WR, MV Sep-May	Coastal, inland; sandy beaches	Hovers and plunge-dives	--

Table 9.3. (Continued).

Species	Seasonality*	Primary Habitat(s)	Foraging	Category of Concern†
Forster's Tern (*Sterna forsteri*)	WR, MV Jul-May	Coastal and inland	Hovers, dips to surface, and plunge-dives	--
Gull-billed Tern (*Sterna nilotica*)	SR, WR, MV Breeds:inland north of study area	Lowland coasts, estuaries, inland lakes, marshes, etc.	Dips to surface, plunge-dives, "hawks" for insects, walks/runs for prey, swoops for prey on ground/water	--
Least Tern (*Sterna antillarum*)	SR Mar-Oct	Coastal and inland	Hovers, dips to surface, and plunge-dives	T - FGFWFC
Roseate Tern (*Sterna dougallii*)	SR, WR, MV Breeds:May-Aug	Exclusively maritime; shallow, sandy areas, shingle beaches	Hovers, plunge-dives, dips to surface, follows schools of large fish; reef's edge and into Gulf Stream	T - FGFWFC T - USFWS
Royal Tern (*Sterna maxima*)	Common all year Most numerous when WRs from north present	Inshore waters, coastlines, estuaries; uncommonly? offshore	Plunge-dives, hovers, and aerial skims	--
Sandwich Tern (*Sterna sandvicensis*)	SR, WR, MV	Inshore, coastal waters, estuaries, sand bars, and humps	Hovers and plunge-dives	--
Skimmers				
Black Skimmer (*Rynchops niger*)	PR, WR Breeds: May-Aug	Beaches, sand bars, spoil islands, parking lots, etc. in daytime	Skims water surface, mandibles agape, longer lower one in water; crepuscular, nocturnal; diurnal to some extent	--

* AV = Accidental Visitor; CV = Casual Visitor; MV = Migratory Visitor; PR = Permanent Resident; SR = Summer Resident; WR = Winter Resident.

† E = Endangered; T = Threatened; SSC = Species of Special Concern; UR2 = Under review for listing, but substantial evidence of biological vulnerability and/or threat is lacking; UR5 = Still formally under review for listing, but no longer considered for listing because recent information indicates species is more widespread or abundant than previously believed; Schedule I = Species with greatest threat of extinction; Schedule II = Species under threat; FGFWFC = Florida Game and Fresh Water Fish Commission; USFWS = U.S. Fish and Wildlife Service.

Cormorants (Family Phalacrocoracidae)

Cormorants submerge and then pursue prey underwater. They seize prey between powerful mandibles. Prey are brought to the surface before they are ingested. One species, the **Double-crested Cormorant** (*Phalacrocorax auritus*), is a Permanent Resident and Winter Resident in the study area; it is included in the species profiles (**Appendix B**). Another species, the **Great Cormorant** (*P. carbo*), is a very casual Winter Visitor.

Anhingas (Family Anhingidae)

Anhingas, like cormorants, forage underwater and rise to the surface to ingest their prey. Unlike cormorants, however, they usually impale fish upon their mandibles. They have areas of plumage that are "wettable" and which function to reduce buoyancy during underwater stalking of prey (Owre 1967). Anhingas frequent freshwater habitats, but also enter quiet, brackish and marine waters. They nest amidst colonial waterbird colonies in mangrove areas. One species, the **Anhinga** (*Anhinga anhinga*), occurs in the study area as a Permanent Resident and Winter Resident.

Frigatebirds (Family Fregatidae)

Frigatebirds are very large, aerial marine birds. Mainly tropical and subtropical, they range the oceans of the world. Their powers of flight are noteworthy. Prey are taken while the frigatebird is in flight. Frigatebirds are kleptoparasites at seabird nesting colonies. One species, the **Magnificent Frigatebird** (Man-O'-War Bird) (*Fregata magnificens*), occurs in the study area and is included in the species profiles (**Appendix B**).

Herons and Allies (Wading Birds) (Order Ciconiiformes)

The "long-legged" wading birds (e.g., herons, ibises, and storks of the Order Ciconiiformes) are distinct from the short-legged wading species (e.g., plovers and sandpipers of the Order Charadriiformes). The former are common to both the marine and freshwater wetlands of South Florida, where no less than 12 (20%) of the entire world's species of herons occur. Nowhere in Florida have these birds been more plentiful than around the mangrove-fringed southern tip of the peninsula embracing Florida Bay. Indeed, some of these species have developed "unique subpopulations that are either completely or largely restricted to Florida Bay" (Powell et al. 1982).

Historically, wading bird populations of South Florida were so large that they were profitably harvested for their plumage, which was used in the millinery trade (Pearson 1937) as well as for food; many species were virtually extirpated from the region. With effective protection in the early part of the 20th century, populations began re-establishing themselves. But these never multiplied to historic levels; decreases in numbers set in about 1935 (Kushlan and White 1977), and have continued (Powell 1987). Inherent in the decrease of these populations is attrition of the feeding environment, apparently brought about by management's impedance of freshwater outflow from the Everglades (Powell et al. 1989). Further compromising of this environment (e.g., through widespread pollution) could be catastrophic to the remaining wading bird populations of Florida Bay and South Florida. Birds that forage in shallow littoral waters, salt marshes, on tidal flats, and within the mangrove wetlands will be at risk from floating oil. It is to be emphasized that many of these long-legged waders will congregate where there are concentrations of prey.

Bitterns, Egrets, and Herons (Family Ardeidae)

Herons have long, pointed mandibles, long legs, and outstandingly long necks; their tails are short and their bodies are slim. Many develop plumes on their head, neck, or back at breeding. Some species occur as adults in more than one color phase (e.g., the Reddish Egret, which is either permanently white or reddish-brown). In some species, immature birds have very different plumage from adults (e.g., the Little Blue Heron, which is white when immature, quite different from the adult).

Wading birds (e.g., herons) have quite different spectra of feeding methods. Some emphasize "standing and wading" for their prey, or they "walk slowly" looking for it. Some are more versatile, using a variety of foraging methods which may include "running," "wing-flicking," "shuffling feet," and even "diving."

Many heron species are colonial at breeding and gather in large rookeries, usually in trees surrounded by water. Many are gregarious at roosting. In foraging, however, most species tend to be solitary or at least spaced apart from each other; nonetheless, when prey is localized and abundant, feeding groups (often of mixed species) may form.

"Herons have always enjoyed a high P.R. rating among wildlife conservationists" (Peterson 1984). It is interesting to realize that the Audubon movement, and in considerable extent the conservation movement early in the Century, were accelerated by the dramatic plight of the wading birds caused by the "plume-hunters."

One bittern, six "egrets," two herons, and two night-herons are found in the study area (**Table 9.3**).

The **Least Bittern** (*Ixobrychus exilis*) is found in the study area as a Summer Resident. Bowman and Bancroft (1989) reported the first nestings in Florida Bay, these on mangrove islets. This is a heron of the lower story of the marsh; it is seldom far from water.

Six herons (designated "egrets") are found in the study area: **Cattle Egret** (*Bubulcus ibis*), **Great Egret** (*Casmerodius albus*) (= American Egret, Common Egret, Great White Egret), **Reddish Egret** (*Egretta rufescens*) (formerly *Dichromanassa rufescens*), and **Snowy Egret** (*E. thula*). The Reddish Egret and Snowy Egret are Florida Species of Special Concern (FGFWFC 1989). The **Tricolored Heron** (*E. tricolor*) and the **Little Blue Heron** (*E. caerulea*) are now regarded as having affinities with certain of the so-called egrets and are treated as "congeneric" with them (AOU 1983); both are designated Florida Species of Special Concern (FGFWFC 1989).

Additional species of ardeids found in the study area include **Great Blue Heron** (*Ardea herodias*) (blue color morph and white color morph--the latter formerly Great White Heron - *A. occidentalis*); **Green-backed Heron** (*Butorides striatus*); and two night-herons: **Black-crowned Night-Heron** (*Nycticorax nyctanassa*), and **Yellow-crowned Night-Heron** (*N. violaceus*).

Ibises and Spoonbills (Family Threskiornithidae)

Large wading birds of powerful flight, ibises and spoonbills are characteristic of warm to temperate, subtropical, and tropical regions (see **Table 9.3**). Ibises have long, thin, decurved bills adapted for "picking," "probing," and "scything" in shallow water. Two species, **Glossy Ibis** (*Plegadis falcinellus*) and **White Ibis** (*Eudocimus albus*), are found in the study area and are included in the species profiles (**Appendix B**).

Spoonbills have flattened, spatulate-shaped bills primarily used in "scything" for small fish. All exhibit pronounced post-breeding and post-fledging dispersal as well as nomadism. One species, the **Roseate Spoonbill** (*Ajaia ajaja*), occurs in the study area. The Roseate Spoonbill is a Species of Special Concern (FGFWFC 1989).

Storks (Family Ciconiidae)

Storks are large wading birds of temperate, subtropical, and tropical regions of the world. Of 17 species, only the **Wood Stork** (*Mycteria americana)* is found in North America. The Wood Stork, an Endangered species, is a Permanent Resident of the study area (**Table 9.3**). From 1967 to 1982, South Florida's Wood Stork population decreased about 75% (Kushlan and Frohring 1986). The population has apparently shifted nesting northward into northern Florida, Georgia, South Carolina, etc. (Frederick and Collopy 1988). Altered hydrography has so changed seasonal water levels that now there is inadequate available food at nesting time (Ogden 1985). Reduced numbers continue to nest at some traditional sites in mangrove swamps between Cape Sable and Maderia Bay (e.g., Lane River, Old Lane River, East River, Cuthbert Lake, and Alligator Lake). The storks did not nest historically on mangrove islets in Florida Bay and have been uncommon on the Keys. Mangrove-nesting birds forage extensively in freshwater drainage systems that terminate at Florida Bay; here, as water levels dropped in winter and spring, prey became trapped in isolated ponds in depressions of the substrate and were available to foragers. Both in and out of nesting season, storks also forage in the mangroves and near the peninsula's southern rim.

Nesting onset in Wood Storks is variable, being dependent upon falling water levels in the Everglades drainage system. Nesting assemblages may form from November to January, and as late as mid-April (Frederick and Collopy 1988). Juveniles disperse widely from the area. Some birds are usually present in the general area outside of the nesting season.

Nesting rookeries of Wood Storks are usually sufficiently inland that oil penetration to them is unlikely. Foraging birds along the mangrove fringe would certainly be vulnerable in the event of a spill. Because this is an Endangered species, *any* unnatural mortality to the population is of concern. Mortality would be particularly serious in view of this being a so-called "K-selected" species which is characterized by deferred maturity, long nest life of young, and extended parental care.

Waterfowl (Order Anseriformes, Family Anatidae)

The wild populations of the waterfowl of North America include more than 40 species. Breeding by most of these is largely confined to central or northern portions of the continent. Most are highly migratory, seeking open water and adequate foraging areas in which to winter.

Several so-called migration "corridors" describe the major flight paths within which southbound waterfowl channel their flight; some of these terminate in Florida; others continue through the State and southward (see Gusey 1981 figs. 1.14, 1.15, 1.16). Of the large numbers of waterfowl of many species arriving in the State, the great majority of individuals "drop out" before they reach South Florida. Gusey (1981) stated that only the **Lesser Scaup** (*Aythya affinis*) "can be considered as occurring regularly in winter along the southern Florida coast." This is not exactly the case. The **Blue-winged Teal** (*Anas discors*), for example, winters largely south of Florida (and the rest of the U.S.), but major migration corridors pass through the State and many migrants pause within the peninsula (Bellrose 1980) including South Florida in the study area. Of the duck species with large North American populations, most are represented, if variably, by at

least some populations which winter in South Florida. Kushlan et al. (1982) listed 22 species of ducks (nearly half of the total North American species) as occurring in Everglades' estuaries. The six species consistently present year by year, and comprising 99% of the numbers of individuals are as follows: Blue-winged Teal, Lesser Scaup, **Northern Pintail** (*Anas acuta*), **American Wigeon** (*Anas americana*), **Ring-necked Duck** (*Aythya collaris*), and **Northern Shoveler** (*Anas clypeata*). Additional species that were noted during Christmas Bird Counts (CBCs) (>90% of the CBCs) included the **Mottled Duck** (*Anas fulvigula*), **Ruddy Duck** (*Oxyura jamaicensis*), and **Red-breasted Merganser** (*Mergus serrator*). Kushlan's census area embraced almost all the inshore coastwise and estuarine surfaces within the study area. Waterfowl being powerful flyers, practically all of the North American species have been recorded in South Florida. Most Casual Visitors and Accidental Visitors are not discussed herein, although several of these species with moderate numbers are included. Only two species of waterfowl breed in South Florida: the **Wood Duck** (*Aix sponsa*), which is not coastal in distribution; and the Mottled Duck which nests inland and, to some extent, in coastal situations.

Swimming birds that spend a great deal of time in the water (e.g., either foraging, loafing, and/or even sleeping) are obviously vulnerable to oil pollution. King and Sanger (1979) rated 33 species of waterfowl with oil vulnerability indexes between 32 and 75. This spread of values derives from differences in the species abundances, seasonality, and adaptations. Chief among the latter are adaptations for foraging: some species dive for their food (= diving ducks); and others reach downward from the surface, their tails then "tipping" upwards (= dabbling ducks). Many species are gregarious outside of breeding and these may "raft" on the water in large numbers. Some species sleep at sea in inshore coastal waters. Manner of taking flight can be important, too: some must make long runs into the wind before becoming airborne, while others launch themselves almost vertically upward into flight.

Finally, it should be realized that the environments wherein species spend the winter or pause to rest and feed while in migration are of no small significance in the maintenance of the continent's waterfowl population.

Within the study area, waterfowl distribution varies (see **Table 9.3**). Most waterfowl are attracted to inland lakes and shallow bights north of Florida Bay's central area. Lakes and mudflats of Cape Sable, especially the areas near Flamingo, attract high but yearly fluctuating numbers.

Vultures, Hawks, and Falcons (Order Falconiformes)

Predators and scavengers, the diurnal birds of prey, have significant roles in population dynamics of continental faunas. South Florida, in addition to its permanently resident falconiforms, has species which migrate here either to breed, to remain as Summer Residents or Winter Residents, or to pass through as Migratory Visitors. Both Migratory Visitors and Winter Residents may be present seasonally in considerable numbers.

Migrating hawks and falcons more or less accompany migrants of the avian taxa upon which they feed. These prey species (e.g., ducks, swallows, flycatchers, warblers, and thrushes) frequently congregate about estuaries and bays, at the termini of land masses, and on islands, etc.; the predators gather where prey can be found. The keys, islets, and mangrove fringes of the peninsula's southern rim become "jumping-off" places for great numbers of land-bird migrants which have paused to rest and forage before departing southward in fall, or north in spring. Shorelines, mudflats, and exposed tidal areas are jumping-off places for plovers, sandpipers, and other shorebirds. Florida Bay, its estuaries, the mangrove lakes, etc. are departure sites for waterfowl and other aquatic

birds. Predators forage for prey concentrated in these places. Page and Whitacre (1975) estimated that birds of prey captured as much as 21% of one species of shorebird during five winter months at a California lagoon. Not all of the predators, of course, are foraging for avian prey. Some are specialized to capture fish. Many capture a variety of vertebrates and invertebrates. Some are primarily, or only occasionally, scavengers.

Oil pollution within the study area would directly affect those species diving for fish (the Osprey), or plucking fish from the water (Bald Eagle). Birds and fish, weakened incidental to oiling, would be the most readily selected prey by foraging falconiforms; the predators might now become oiled from handling such prey and/or affected from ingesting them. The falcons (Peregrine) may knock or drive their prey into the water and then retrieve such. It follows that they would become oiled. For the scavengers (vultures, eagles, gulls, and others), carcasses, even though oil-soaked, would be prime attractants with obvious, possibly serious results. It needs to be emphasized that at times of the year, portions of the study area have concentrations of hundreds, even thousands of predators and their prey. The potential for widespread avian mortality would certainly exist.

It is to be stressed that predators and prey under discussion represent nesting populations of the tundras of Alaska, Canada, and even Greenland, of the taiga and the boreal forests of North America, the prairies of the middle portion of the continent, the deciduous forests of the Southeast, in addition to habitats of Florida itself. Both migrating and wintering predators can be concentrated in numbers; many may pass through an area within short periods of time. Widespread mortality here in the study area could affect local nesting populations from throughout the North American continent.

Numbers of the Falconiformes have been seriously reduced by human pressures. Throughout the world, large-scale hunting has gone on since settling of the continents. One can describe such hunting of earlier times as a purposeful onslaught to eliminate the predators. Persistent pesticides have destroyed or reduced fertility of large numbers of the birds. Habitat destruction has much reduced populations. Populations of many species have been so reduced that in Europe, for example, of 29 regularly breeding species, 17 have declined markedly in numbers (Cramp et al. 1980); here in South Florida, seven of the falconiform species encountered within the study area are included in Categories of Concern (FGFWFC 1989). Unusual sources of mortality, sources not ordinarily presented by the environment, are of real cause for concern with respect to "stressed species" as are many of the Falconiformes.

Vultures (Family Cathartidae)

Among the very largest of North American birds, vultures have exceedingly light wing-loading, and their powers of soaring flight are outstanding. The great mobility of the birds makes it possible for them to gather quickly at dead or dying animals that appear in the landscape. The birds could be attracted to fish, birds, and other animals sick or dead from the effects of oil pollution.

Two species of vultures occur in Florida, the **Black Vulture** (*Coragyps atratus*) and the **Turkey Vulture** (*Cathartes aura*). Both are present within the study area (**Table 9.3**). The Turkey Vulture is of more than considerable interest with respect to olfactory abilities, its two subspecies within the study area, and an apparently sedentary population as well as large wintering population derived from much of northeastern North America.

Kites, Eagles, Hawks, and Allies (Family Accipitridae)

Adaptive radiation within the hawk family has evolved pronounced "types" of these diurnal predators; their morphology and foraging methods are keyed to types of prey. The smallest hawk in the study area, the **Sharp-shinned** (*Accipiter striatus*) (which may weigh as little as 100 g), is a "bird hawk" of the genus *Accipiter*. Characterized by short, rounded wings and a long tail, accipiters are wonderfully maneuverable in flight, being able to pursue small birds around bushes and among the trees. Even more maneuverable are the kites. The **American Swallow-tailed Kite** (*Elanoides forficatus*) (occurring within the study area) twists, turns, and pivots in flight as it plucks dragonflies from the air or small birds from outer canopies of the trees. The Endangered (USFWS, FGFWFC) **Snail Kite** or **Everglades Kite** (*Rostrhamus sociabilis*) is a highly specialized kite of Florida. It forages only for apple snails (*Pomacea* sp.), which are strictly freshwater inhabitants. This kite may infrequently enter the study area; it is essentially a bird of the central and northern portions of the Everglades basin. The **Red-shouldered Hawk** (*Buteo lineatus*), **Broad-winged Hawk** (*Buteo platypterus*), and others of the genus *Buteo* circle high in the sky, perch in the open or in the forest canopy, and pounce on prey on the ground. The **Bald Eagle** (*Haliaeetus leucocephalus*), an Endangered (USFWS) and Threatened (FGFWFC) species, is the largest of the accipitrids in the study area; females may weigh up to 17 kg. This raptor, a bird of estuaries, lakes, and marine or freshwater littorals, has a diversity of foraging strategies; it picks up fish from the water's surface, captures wounded ducks and other such available prey, scavenges beaches, and is a kleptoparasite of the exclusively fish-eating **Osprey** (*Pandion haliaetus*), which is a Species of Special Concern.

Resident accipitrids build nests of twigs and sticks. Nests of larger species can be proportionately huge. Placed high in trees, the nests become prominent features of the landscape. Such nests are usually reused in succeeding seasons.

Largely predators of live prey, many accipitrids of northern areas are migratory. As with the falcons in fall and spring, numbers of hawks that do not nest in South Florida, arrive here in migration. Passing through the study area, they forage for traditional prey. Some winter here.

Nine of the accipitrid species found in the study area have been selected for discussion in the species profiles (see **Table 9.3**). Six of these have breeding populations here. One, the American Swallow-tailed Kite, migrates here in spring from South America to breed. Three are exclusively Winter Residents. As with many accipitrids, breeding species may disperse to other areas after nesting, and populations of the same species may migrate here in winter or pass through in migration.

Falcons (Family Falconidae)

The typical falcons are compact, solid birds of prey with long, narrow, pointed wings characteristic of birds capable of high speed. The edge of the upper mandible has a pointed projection (it is "toothed") which is used in tearing flesh.

Falcons in the study area represent three lines of adaptive radiations of the true falcons. The **Arctic Peregrine Falcon** (= Duck Hawk) (*Falco peregrinus tundrius*) is one of the larger falcons that "stoops" on its prey from above; the speed of the stoop is such that when the prey is struck by the falcon's large feet, it is usually killed and tumbles to earth. The falcon then circles, lands, and tears up the prey or picks it up and carries it away to devour. The **Merlin** (*F. columbarius*), a much smaller falcon, overtakes prey in pursuit. Finally, the **American Kestrel** (*F. sparverius*) is representative of small falcons

that hover in the air over open areas and drop on small mammals and insects on the ground.

Falcons found in the northern portions of Eurasia and North America undertake long migrations to winter in areas with adequate food supplies. Many accompany the migrations of prey species of birds and gather at the concentrations of these at stopover places and wintering grounds.

Cranes and Allies (Order Gruiformes)

The Rallidae (rails, coots, gallinules), the Aramidae (limpkins), and the Gruidae (cranes) are the only families of the large Order Gruiformes of concern regarding the study area. Species of coots and rails are listed in **Table 9.3**, along with the Florida Sandhill Crane.

The **Limpkin** (*Aramus guarauna*), a Florida Species of Special Concern (FGFWFC) only occasionally enters mangroves or the habitats of the Keys (Howell 1932); it is not considered in the species profiles (**Appendix B**).

Rails, Coots, and Gallinules (Family Rallidae)

Rails are small to medium-sized, secretive birds of the marshes. Many are nocturnal. When foraging, they use their long, thin bill to pick and probe for invertebrates. Two rails are included in the species profiles (**Appendix B**): (1) the **Clapper Rail** (*Rallus longirostris*), two subspecies of which occur in the study area--the **Florida Clapper Rail** (*R. l. scottii*) and the **Mangrove Clapper Rail** (*R. l. insularum*); and (2) the **Sora** (*Porzana carolina*). The **King Rail** (*R. elegans*) has a habitat interfacing that of the Clapper Rail, but it is largely a freshwater inhabitant; it is not given a species profile. Other rails (not included in the species profiles) are Migratory Visitors or Winter Residents in the study area: **Yellow Rail** (*Coturnicops noveboracensis*), **Black Rail** (*Laterallus jamaicensis*), and **Virginia Rail** (*R. limicola*).

Coots are duck-like swimming birds that dabble and dive for food, usually algae and other plants. They frequently associate with ducks. Coots are often present in very large numbers. The **American Coot** (*Fulica americana*) is included in the species profiles. The **Common Moorhen** (*Gallinula chloropus*) and the **Purple Gallinule** (*Porphyrula martinica*) (neither considered in the species profiles) are found inland in freshwater areas fringing the coast; they seldom enter the brackish and saline coastal swamps.

Rails are vulnerable to oil penetrating the mangroves or marine-bordering marshes. Coots, when congregated in brackish and marine situations, can suffer considerable mortality from oil.

Cranes (Family Gruidae)

Cranes are extremely long-legged omnivores of marshes, grasslands, savannas, and swampy brinks of wetlands. One species, the **Florida Sandhill Crane** (*Grus canadensis pratensis*), is found within the study area. The Sandhill Crane is a Threatened species (FGFWFC). It is essentially a freshwater marsh bird found in the study area near the interface with coastal mangroves. The potential for oiling seems remote.

Shorebirds (Order Charadriiformes)

This large taxon contains more than 300 species. Adaptive radiation of ancestral charadriiforms led to a broad diversification in ways of "making a living" in the marine and marine-bordering ecosystems. The three suborders of the Charadriiformes (i.e., Charadrii, Lari, and Alcae) illustrate this. The suborder Charadrii includes the plovers, sandpipers, and others that pluck, probe, and glean from the substrates they walk or wade in. The Lari (e.g., gulls, terns, etc.) are aerial and forage while in flight. Finally, the Alcae (e.g., auks, dovekies) forage while swimming. Representatives of the Charadrii and Lari are important components of the South Florida avifauna; species of the Alcae reach South Florida only as infrequent Accidental Visitors.

"Shorebirds" ("waders" to Europeans) are mostly smallish birds, foraging on invertebrate faunas around freshwater and marine habitats. While some species nest coastally, most breed in the continents' interiors: marshes, along lakes and rivers, on the prairies, and, in the case of *many* species, on the Arctic tundras. Most species, when they leave their nesting grounds, carry out coastwise and transoceanic migrations, some of which are transequatorial (particularly scolopacid species [sandpipers and allies]). Their destinations are the beaches, bays, and estuaries of coastlines of the continents. As much as two-thirds to three-quarters of the year is spent by most of the species in migration and wintering; for much of the year, then, these birds become components of marine ecosystems (Burger 1984). Only a very few shorebird species nest in South Florida. Many migrate through South Florida, pausing en route to rest and feed (see **Table 9.3**). Senner and Howe (1984) identified northern Florida Bay as an "important, traditional stopover site" for migrating shorebirds in North America. Many winter here in some numbers.

It is important to consider that winter habitat use by these littoral-oriented birds is in large part predicated by tidal cycles. Low tide is the favorable time to frequent beaches and tidal flats. Feeding peaks of many species can be correlated with low tide, when invertebrate prey animals become relatively inactive. Energy demands of these birds are so exacting that 90% of the daylight hours may be spent foraging. Many species forage crepuscularly and nocturnally to take maximum advantage of tidal conditions (Puttick 1984). Because tides change constantly, foraging potential is continually changing, and optimum foraging periods are temporary.

Few avian taxa appear to be at greater hazard to widespread oil pollution than the shorebirds. Oil washing up on beaches during changing tidal stages will destroy the invertebrate fauna the birds prey upon. Also, because the shorebirds forage, loaf, and sleep on the shorelines, their feet and plumage would be very susceptible to oiling. Because shorebirds move about within their wintering area to take advantage of opportunities presented at different places and habitats, they could encounter oil in more than one place. During migration periods, individuals within an area may well be constantly arriving and departing. Burger (1984) called attention to the fact that many shorebirds have fidelity to their specific wintering sites. Until recently, management and conservation officials have not considered the shorebirds as seriously as other taxa of marine birds found along our beaches, bays, estuaries, and inshore waters.

Plovers (Suborder Charadrii, Family Charadriidae)

Plovers are birds of open ground, particularly beaches. They can run swiftly and fly strongly. Foraging is visual, food being picked from the ground or surface of shallow water. Many are active at night as well as day. Six species can be encountered in the study area (**Table 9.3**): **Black-bellied Plover** (*Pluvialis squatarola*), **Killdeer** (*Charadrius vociferus*), **Piping Plover** (*C. melodus*), **Semipalmated Plover** (*C. semipalmatus*),

Southeastern Snowy Plover (*C. alexandrinus tenuirostris*), and **Wilson's Plover** (*C. wilsonia*). Both the Piping Plover and the Southeastern Snowy Plover are categorized by the FGFWFC as Threatened species. The USFWS also categorizes the Piping Plover as Threatened, but the Southeastern Snowy Plover as Under Review.

Oystercatchers (Suborder Charadrii, Family Haematopodidae)

Oystercatchers are among the most spectacular of the large shorebirds. Largely black and white, their legs and feet are pink, their mandibles red-orange. Although heavily built, the birds swim, as well as walk and run, with some agility.

The oystercatcher bill, as long as 10 cm, is laterally compressed and chisel-shaped at the tip. With this bill, the birds can open clams and oysters, and pry attached molluscs from rocky shorelines.

Of two species occurring in the U.S., only the **American Oystercatcher** (*Haematopus palliatus*) occurs in South Florida and the study area (**Table 9.3**). It is a Permanent Resident locally, and occurs in small numbers; however, in winter, its numbers increase. The American Oystercatcher is a Species of Special Concern (FGFWFC 1989).

Stilts and Avocets (Suborder Charadrii, Family Recurvirostridae)

Stilts and avocets are large shorebirds characterized by very long legs, long slender bills, and bold color patterns. Bill lengths of stilts exceed 55 mm and are slightly recurved (upturned) at the tip. Avocet bills exceed 80 mm and are markedly recurved.

Stilts frequent freshwater habitats more than do avocets. In South Florida, they forage in shallow water with margins rimmed with trees, shrubs, or marsh vegetation. Stilts are also found in mangrove ponds and at pools on the coastal prairie. They grasp food at or below the surface. Avocets favor open areas such as mud or marl flats, with alkaline or saline content. Their bills are adapted to gather small organisms from water or soft substrates; they often scrape food from mud and the surface of shallow water.

Of seven recurvirostrid species found in the world, two species (one stilt and one avocet) are found in the study area (**Table 9.3**). The **Black-necked Stilt** (*Himantopus mexicanus*), a Species of Special Concern, is largely a Summer Resident (a few remain in winter), migrating here from South America. The **American Avocet** (*Recurvirostra americana*) is a Winter Resident, migrating to South Florida in small numbers from western North America.

Sandpipers and Allies (Suborder Charadrii, Family Scolopacidae: Scolopacinae)

The more than 50 species of the world's sandpipers present a wide spectrum of body sizes, leg and bill lengths, and foraging methods. The smallest, the **Least Sandpiper** (*Calidris minutilla*), may weigh no more than 20 g and its bill may measure 2 cm. The largest, the **Long-billed Curlew** (*Numenius americanus*), may weigh more than 900 g and its bill length may reach 65 cm; it is not considered in the species profiles (**Appendix B**). The scolopacid species are adapted to utilize a great many ecological niches of littoral, marsh, and prairie ecosystems.

Compared with plovers, the sandpipers have generally longer legs, slimmer bodies, and more slender bills, the latter more or less curved in many species. Sandpipers are less typical of the upper portions of sandy beaches than are plovers. Many species

forage along receding tide lines and on exposed tidal flats. Their foraging is not always entirely visual. Many probe in wet mud.

The common names of sandpipers (e.g., peeps, stints, turnstones, dowitchers, godwits, and curlews) attest to the familiarity of these birds' habits and natural history to hunters, naturalists, and many people who appreciate the birds. Peter Matthiessen (1973) wrote of the sandpipers, "their kinship with the distance and swift seasons, the wistful signal of their voices down the long coastlines of the world make them the most affecting of wild creatures."

More than any other taxon of birds, the scolopacids are travellers across wide arcs of the planet. Many breed on Arctic tundras. The **Red Knot** (*Calidris canutus*), for example, migrates between Alaska and Tierra del Fuego at the southern tip of South America. Its stopover places en route furnish it with the food to replenish the fat which will supply it with energy to fly the long distances at speeds which may exceed 64 km/h (35 knots). It stops each year at the places it has stopped at before. It is important that the scolopacid stopover places and wintering places, as well as breeding grounds, remain free of pollution and contaminants.

Not all of the species of the Scolopacidae that are found in the study area are presented in the species profiles. The wide selection of species presented has been chosen to demonstrate the diversity of habits, origins, and problems these birds may face with respect to oil pollution (see **Table 9.3**).

Gulls (non-pelagic) (Suborder Lari, Family Laridae:Larinae)

Gulls are medium-sized (as a pigeon) to large (1.4 m wingspread) birds. In flight, they are buoyant and utilize thermals and obstruction currents within which to soar to heights which may exceed 600 m (Woodcock 1940). By alternating soaring to heights and protracted glides downward, the birds can cover considerable distances with little actual expenditure of energy. They walk well and swim with webbed feet. In migration, they tend to follow coastlines, scavenging on littoral animals and tidal wash-ups. Gregarious, they nest colonially and roost on land and water in company with others.

Gulls are omnivores that use whatever methods are appropriate for the foraging situations (Burger 1988). The most frequently used method is "picking" items from the surface (48% of the time) or "surface dipping" (21%) (see Burger 1988). Primary food items are insects, crustaceans, snails, worms, other invertebrates, fish, sewage and garbage dump items, and carcasses.

Four species of non-pelagic gulls are presented in **Table 9.3**. Only the **Laughing Gull** (*Larus atricilla*) breeds in the study area. Another species, the **Ring-billed Gull** (*L. delawarensis*), winters in large numbers. The **Herring Gull** (*L. argentatus*) is ubiquitous in winter, but occurs in small numbers. **Bonaparte's Gull** (*L. philadelphia*) is a regular Winter Resident, but in very small numbers. The **Great Black-backed Gull** (*L. marinus*) (not discussed in the species profiles) is extending its breeding range southward along the Atlantic coast and now appears infrequently in winter. Gulls are wanderers along the littoral pathways and are often caught up in weather masses (e.g., hurricanes which can entrap birds over large areas); numerous other species, not discussed in the species profiles, are Casual Visitors and Accidental Visitors in South Florida.

Terns (Suborder Lari, Family Laridae:Sterninae)

Terns are distributed along the seacoasts, throughout the freshwater wetlands, and over the oceans of the world. While the majority of species are adapted to warm or tropical regions, some breed at high latitudes and are highly migratory as indeed are some of the pelagic species of subtropical/tropical ocean masses. A number of the species of the Northern Hemisphere breed in both North America and Eurasia, the geographical populations of these species having specific migratory routes and wintering areas.

Terns forage on small fish and other life at the air/water interface. Most characteristically, terns "plunge-dive" from altitudes of a very few meters, the dive resulting in partial or complete submergence; in either case, the dives are shallow ones and the birds rise from the water with rapidity. Terns also "dip to the surface" for food items and they may seize prey such as insects from the air.

More delicately built than gulls, terns have longer and narrower wings and their flight is faster and more buoyant. They seldom soar and glide as gulls; rather they beat their wings constantly. With shorter legs and smaller feet, terns swim less than gulls and seldom forage while walking.

A maritime habitat usually has several species of terns which differ markedly in body and bill-size. Ashmole (1968) showed that ecological segregation among sympatric species is achieved by these differences in sizes which correlate with prey sizes.

Most terns nest on the ground, often on undisturbed beaches or shoreline areas. Their populations have been much reduced: first, the birds were harvested for their feathers (millinery trade); then, eggs were taken from the breeding colonies; and finally, their habitats were destroyed by man. Numbers of tern species have never regained abundances they once had.

Fourteen species of terns occur in South Florida. Eleven are listed in **Table 9.3**; the other three, the Black Noddy, the Brown Noddy, and the Sooty Tern, have been discussed in the Dry Tortugas section and are included in **Table 9.2**). Four of the 14 species occur as migrants, and four nest within the study area. Two nest north of the study area, one nests nearby in the Caribbean and reaches the study area with some regularity, while others winter here. Of terns in the study area, two are in Categories of Concern: the **Least Tern** (*Sterna antillarum*) (classified by the FGFWFC as Threatened), and the **Roseate Tern** (*S. dougallii*) (classified by both the FGFWFC and USFWS as Threatened).

Skimmers (Suborder Lari, Family Laridae:Rynchopinae)

The world's three species of skimmers forage by flying very low, with the elongated lower mandible held in the water and the upper mandible elevated. When small fish or other prey are encountered, the mandibles snap shut. Skimmers are crepuscular and nocturnal in foraging, occasionally diurnal. The **Black Skimmer** (*Rynchops niger*), which occurs in the study area, is a Winter Resident as well as a Permanent Resident (**Table 9.3**). A small number has been found breeding in the Dry Tortugas.

LAND BIRDS

Well more than 100 species of "land birds" occur within the study area. Those considered here represent seven orders: Columbiformes (Pigeons), Cuculiformes (Cuckoos), Strigiformes (Owls), Caprimulgiformes (Nighthawks), Coraciiformes (Kingfishers), Piciformes (Woodpeckers), and Passeriformes (Passerine Birds).

Land birds typically are not modified for aquatic life. Birds that live in the canopy of the mangrove trees, for example, are integral parts of an ecological community, a marine swamp forest. The hardwood tropical forests of the Florida Keys are not as obviously marine-influenced as are the mangroves, but here too, marine factors influence their existence. It is difficult to envision any habitats within or close by the study area that would not be strongly influenced by activities coincident to oil prospecting, storage, and transportation. Degradation of mangroves and nearby terrestrial habitats could affect portions of land bird populations of the study area.

Land birds in the study area can be grouped into five categories (**Table 9.4**):

- The West Indian avifaunal element. Considerable interest is attached to birds of this category. Records of recent decades show that numerous West Indian species reach South Florida rather regularly (Robertson and Kushlan 1974). Over time, some of these have obviously been able to colonize the Keys and the southern rim of the peninsula. Some colonizations have spread northward in Florida. The species profiles (**Appendix B**) contain information about species whose populations (outside of West Indian areas) are either entirely or largely restricted to the study area or, if they have extended their ranges northward, are represented in the study area by substantial populations. Examples are **Antillean Nighthawk** (*Chordeiles gundlachii*), **Mangrove Cuckoo** (*Coccyzus minor*), and **Mourning Dove** (*Zenaida macroura macroura*).

- Endemic subspecies. These are birds that, although representative of species of the North American avifauna, are recognizable subspecies endemic to the Florida Keys and the nearby mainland. Found on the Keys and adjacent parts of the peninsula are subspecies adapted to the sub-tropical conditions of these areas. These populations are, of course, unique. Large-scale degradation of coastal ecological communities could endanger these birds. Examples are **Cape Sable Seaside Sparrow** (*Ammodramus maritimus mirabilis*) and **Prairie Warbler** (*Dendroica discolor paludicola*). The Cape Sable Seaside Sparrow is an Endangered species (USFWS and FGFWFC).

- Migrants that pass through the study area in spring and/or fall. Many species of land birds pass across the Gulf of Mexico to and from wintering ranges in South America. Smaller numbers of species, but often represented by large populations, migrate through the Florida peninsula to and from the West Indies and/or South America. Some species of the latter group could be affected by changes in the ecology of the marine-bordering habitats of the study area. Examples are **Barn Swallow** (*Hirundo rustica*) and **Cape May Warbler** (*Dendroica tigrina*).

Table 9.4. Land birds known to occur in the study area.

Species	Seasonality*	Primary Habitat(s)	Foraging	Category of Concern+
WEST INDIAN ELEMENT				
Antillean Nighthawk (*Chordeiles gundlachii*)	SR, Apr-Sep Breeds: May-Jul	Open areas for ground nesting-landfills, scarified ground, pastures, etc.	In flight, pursues insects	--
Black-whiskered Vireo (*Vireo altiloquus*)	SR Apr-Sep	Mangroves and some neighboring growth	Canopy gleaner	--
Cuban Yellow Warbler (*Dendroica petechia gundlachi*)	PR (since 1943) Breeds: Jan-Jul	Mangroves	Forages canopy for invertebrates	--
Gray Kingbird (*Tyrannus dominicensis*)	SR Breeds: May-Jul	Mangroves, pineland, urban areas, etc.	"Hawks" for insects	--
Mangrove Cuckoo (*Coccyzus minor*)	PR Breeds: May-Jul	Mangroves, tropical hammock, and beach scrub	Arboreal-gleans	--
Mourning Dove (*Zenaida macroura macroura*) (a West Indian subspecies)	PR Breeds: many months	Open, terrestrial areas	Ground-forages on grain and seeds	--
Smooth-billed Ani (*Crotophaga ani*)	PR Breeds: Mar-Nov	Open areas with scattered growth, gardens, fields, and clearings	In flocks through low growths & on ground, for insects (especially grasshoppers & lizards)	
White-crowned Pigeon (*Columba leucocephala*)	PR, SR	Mangroves (nests) and neighboring upland	Arboreal; frugivorous	T - FGFWFC UR2 - USFWS
ENDEMIC SUBSPECIES				
Cape Sable Seaside Sparrow (*Ammodramus maritimus mirabilis*)	PR Breeds: Feb-Aug	Formerly found in *Spartina* marsh, Cape Sable; now in East Everglades and Big Cypress areas (freshwater)	On ground, for small invertebrates	E - FGFWFC and USFWS
Prairie Warbler (*Dendroica discolor paludicola*)	PR Breeds: Feb-Jul	Mangroves	Gleans for small invertebrates	--
MIGRANTS				
Barn Swallow (*Hirundo rustica*)	MV Jul-Oct	Air space low over the study area; may roost in mangroves or other trees	While in flight, for insects	--
Blackpoll Warbler (*Dendroica striata*)	MV Apr-May	Forest canopy - roosting and foraging	Forages in canopy	--

Table 9.4. (Continued)

Species	Seasonality*	Primary Habitat(s)	Foraging	Category of Concern†
Bobolink (*Dolichonyx oryzivorus*)	MV Apr-May Aug-Oct	Air space and open ground with low growth (grasses) for foraging	On ground, for seeds and insects	--
Cape May Warbler (*Dendroica tigrina*)	MV	Forest canopy - roosting and foraging	Forages in canopy for insects, worms, berries	--
WINTER RESIDENTS				
Belted Kingfisher (*Ceryle alcyon*)	WR, MV Aug-Nov Mar-May	Clear water (marine, fresh) with suitable perches immediately nearby	Hovers, plunge-dives	--
Blue-gray Gnatcatcher (*Polioptila caerulea*)	WR Jul-Apr	Mangrove forests, tropical hammocks, surburban landscaping, and parks	Gleans leaves for invertebrates; fly-catches	--
Palm Warbler (*Dendroica palmarum*)	WR, MV Sep-May	The landscape, needs open spaces and roosting trees	The ground, fields, upper littoral areas, etc. for insects	--
Tree Swallow (*Tachycineta bicolor*)	WR Aug-May	The landscape plus roosting trees, fruiting trees; insects	While in flight, forages for insects; settles on fruiting bushes, trees for fruit	--
Yellow-bellied Sapsucker (*Sphyrapicus varius*)	WR Oct-May	Mangroves, tropical hammocks, and trees anywhere	Drills sapwells from which forages for sap	--
PERMANENT RESIDENTS				
Burrowing Owl (*Athene cunicularia*)	PR Breeds: Nov-May	Open ground with depth of soil for burrows: landfills, prairies, etc.	Crepuscularly and nocturnally, short flights to capture prey on or near ground	SSC - FGFWFC
Red-bellied Woodpecker (*Melanerpes carolinus*)	PR Breeds: Feb-Jul	Densely or sparsely wooded areas	Tree trunks, and fruiting trees and shrubbery	--
Red-winged Blackbird (*Agelaius phoeniceus*)	PR Breeds: May-Jul	Marshes, swampy habitat; also pastures, lawns, and open ground	Within aquatic vegetation and on open ground	--
White-eyed Vireo (*Vireo griseus*)	PR Breeds: Feb-Jul	Understory thickets and bushes	Hunts and gleans methodically through foliage	--

* MV = Migratory Visitor; PR = Permanent Resident; SR = Summer Resident; WR = Winter Resident.
† E = Endangered; T = Threatened; SSC = Species of Special Concern; UR2 = Under review for listing, but substantial evidence of biological vulnerability and/or threat is lacking; FGFWFC = Florida Game and Fresh Water Fish Commission; USFWS = U.S. Fish and Wildlife Service.

While some species, depending upon weather conditions and their physiological states, overfly the areas without stopping, others stop and remain for periods within the marine-bordering habitats to rest, feed, and build up fat reserves necessary for their long flights and to await appropriate meteorological conditions for resumption of their journeys. Mangrove forests, tropical hammocks, salt marshes, coastal prairies, etc., are landfalls for many migrants coming from the south. Since these birds, often flying against headwinds, can be approaching exhaustion, food and shelter are vital for continued migration.

- Land birds wintering in the study area. Within the study area are numerous land birds dependent upon the habitats for appropriate foraging and shelter during a part of the year. Some, before migrating in spring, build up the fat that will help sustain them in their northward migrations as well as possibly maintain them briefly in their breeding habitats if these are ecologically unsuitable when they arrive. Examples are **Belted Kingfisher** (*Ceryle alcyon*), **Blue-gray Gnatcatcher** (*Polioptila caerulea*), and **Yellow-bellied Sapsucker** (*Sphyrapicus varius*).

- Permanent residents common to the southeastern U.S. and South Florida. Land birds discussed here are Temperate Zone species representative of species Permanently Resident on the Florida peninsula; their ranges extend onto the Florida Keys. They are integral parts of the ecological communities of the study area. Examples are **Burrowing Owl** (*Athene cunicularia*), **Red-winged Blackbird** (*Agelaius phoeniceus*), and **White-eyed Vireo** (*Vireo griseus*).

Any considerable alteration of the ecology of the land birds' marine-bordering habitats can affect their populations. The energy these birds require is derived from the plant and animal products of the habitats. This energy may be critical to their reproduction, their migrations, and their very survival. The habitats afford them the shelter an animal requires. Many of these populations are unique. The species represented are "fine-tuned," so to speak, in their adaptations as well as in their "traditions" to this very small place in the world.

Pigeons and Doves (Order Columbiformes, Family Columbidae)

Pigeons and doves are not usually considered in the context of maritime birds. Two species of this family, representative of the West Indian avifauna, however, can be of concern in relation to oil and gas operations in the study area. The **White-crowned Pigeon** (*Columba leucocephala*), a Species of Special Concern, breeds on mangrove islets along the extent of the Florida Keys to the Marquesas, throughout Florida Bay, and along the southern rim of the peninsula. A portion of the breeding population migrates to winter in Cuba, the Bahamas, and other Caribbean islands where others of the species nest. The White-crowned Pigeon is a unique component of the mangrove ecosystem (Owre 1978). Elsewhere in its range, the species has experienced drastic declines in numbers and has been extirpated from some islands (Wiley and Wiley 1979). Florida is one of few places where adults and squabs are not hunted. Long-term damage to and/or disturbance within large areas of the red mangroves would be serious for this population.

The West Indian subspecies of the **Mourning Dove** (*Zenaida macroura macroura*), a Permanent Resident of the area, is abundant throughout the Keys and adjacent portions of the peninsula. Mourning Doves are foragers in upland areas, and vulnerability to oil spills would seem remote; they would respond, however, to degradation of land areas.

Cuckoos and Anis (Order Cuculiformes, Family Cuculidae)

Cuckoos are widely distributed over the world. Most species are arboreal, but a few, such as the Roadrunner, are terrestrial. The arboreal species are secretive and spend much of their time in thick foliage where they specialize in foraging for caterpillars and other insects. Their loud, unmusical calls are startling.

Three arboreal cuckoos occur in the study area. The **Yellow-billed Cuckoo** (*Coccyzus americanus*) is a spring-fall migrant and a Summer Resident. The **Black-billed Cuckoo** (*Coccyzus erythropthalmus*) is a spring-fall migrant. The **Mangrove Cuckoo** (*Coccyzus minor*), the only cuckoo discussed in the species profiles (**Appendix B**), is a West Indian, Central, and South American bird found also in South Florida. It is, to a large extent, a bird of the mangrove forest. The **Smooth-billed Ani** (*Crotophaga ani*) is a bird of open areas where it moves about in small groups. Its affinities lie to the south of Florida and it appears to have introduced itself into the State.

Owls (Order Strigiformes, Family Strigidae)

Two large owls of this family of nocturnal raptors are found throughout the mainland rim of the study area: the **Great Horned Owl** (*Bubo virginianus*) and the **Barred Owl** (*Strix varia*). A medium-sized owl, the **Barn-owl** (*Tyto alba*) (of the owl family Tytonidae), and two additional species, the **Short-eared Owl** (*Asio flammeus*) and the **Eastern Screech-owl** (*Otus asio*), occur infrequently in the Florida Keys. The **Burrowing Owl** (*Athene cunicularia*), the only owl discussed in the species profiles (**Appendix B**), is a Species of Special Concern found in the study area.

Nighthawks (Order Caprimulgiformes, Family Caprimulgidae)

In nighthawks, the gape (mouth opening) is very large. Insects and even very small flying birds are caught as the birds dart about in flight. Caprimulgids are nocturnal, and they nest on the ground.

Most North American species, including the four found in Florida, are highly migratory, wintering in South America. The **Antillean Nighthawk** (*Chordeiles gundlachii*), described in the species profiles (**Appendix B**), occurs locally in South Florida and the study area.

Kingfishers (Order Coraciiformes, Family Alcedinidae)

Some species of kingfishers are atypical land birds in that they forage within aquatic situations for their food. The **Belted Kingfisher** (*Ceryle alcyon*), discussed in the species profiles (**Appendix B**), breeds throughout a large portion of North America. It nests in holes which it digs in hillsides, highway cuts, etc. Northern birds are highly migratory and winter in areas of open water.

Woodpeckers and Sapsuckers (Order Piciformes, Family Picidae)

Woodpeckers are adapted to forage upon tree trunks and branches. Adaptations include clinging to bark and propping themselves against it as well as chiseling and excavating into wood for insects and their larvae; some excavate holes in bark to obtain sap. Most will eat berries. Woodpeckers are important residents of forests everywhere, including mangrove forests and neighboring tropical hammocks of the study area.

Two species are included in the species profiles (**Appendix B**): the **Red-bellied Woodpecker** (*Melanerpes carolinus*), a Permanent Resident that excavates for insects and eats fruit; and the **Yellow-bellied Sapsucker** (*Sphyrapicus varius*), a Winter Resident that exploits mangroves and other trees for sap.

Flycatchers (Order Passeriformes, Family Tyrannidae)

The New World Flycatchers are typically solitary and arboreal. When foraging, they perch in exposed places and dart out in pursuit of passing insects. Northern species are highly migratory and many pass through South Florida en route to and from South America. A few, such as the familiar **Phoebe** (*Sayornis phoebe*), winter here; it is not included in the species profiles (**Appendix B**). The **Gray Kingbird** (*Tyrannus dominicensis*), discussed in the species profiles, migrates from South America to breed in South Florida, particularly in and about the mangrove forests.

Swallows (Order Passeriformes, Family Hirundinidae)

Swallows are among the most aerial of birds, most of their daytime hours being spent in the air. Foraging is entirely on the wing.

Of the nine species found north of Mexico, two are discussed in the species profiles (**Appendix B**). A part of the population of the **Barn Swallow** (*Hirundo rustica*) funnels through Florida and goes southward into South America, returning in spring. The **Tree Swallow** (*Tachycineta bicolor*) winters in large numbers in the study area.

Old World Warblers (Order Passeriformes, Family Muscicapidae: Sylviinae)

There are only a few representatives of the Old World Warblers in North America. These are tiny, extremely active insectivorous birds. The **Blue-gray Gnatcatcher** (*Polioptila caerulea*), discussed in the species profiles (**Appendix B**), is a Winter Resident of the study area. It holds a territory on its wintering grounds and searches the outer foliage of the tree canopies, bushes, and other dense growth. Occasionally the birds flycatch and eat berries. As most Sylviins, the birds are quite vocal and have an outstanding song.

Vireos (Order Passeriformes, Family Vireonidae)

Vireos are small songbirds of New World forests. Largely insectivorous, most North American species are highly migratory. A few winter in southern states. In Florida, one species, the **White-eyed Vireo** (*Vireo griseus*), is a Permanent Resident. All species are canopy foragers, some high in the tree foliage, some in lower-story forest growth. Deliberate in their activities, all glean for insects and larvae and usually will also eat berries. Two vireos of the study area are discussed in the species profiles (**Appendix B**). The **Black-whiskered Vireo** (*V. altiloquus*) migrates from South America and nests in the mangrove forests. The White-eyed Vireo, a Permanent Resident, forages in bushes and thickets upland of the mangroves. The songs of these two vireos are picturesque parts of the study area's landscapes.

New World Warblers (Order Passeriformes, Family Emberizidae: Parulinae)

More than 50 species of American Wood Warblers are found in North America. Breeding species occur from Alaska and northern Canada southward through the Continent. Northern species of these insectivorous birds are strongly migratory, entire populations of some crossing the Continent to winter in the West Indies and South America. Some of these throng through the study area en route to and from the West Indies and South America. Two, the **Cape May Warbler** (*Dendroica tigrina*) and the **Blackpoll Warbler** (*D. striata*), are discussed in the species profiles (**Appendix B**). Some species, such as the **Palm Warbler** (*D. palmarum*), which becomes very common, winter

in Florida and in the study area (see discussion). One species, the **Cuban Yellow Warbler** (*D. petechia gundlachi*), discussed in the species profiles, is a colonizing species from the West Indies that has established itself in the mangrove forests of the study area. The mangrove forest is the habitat of the endemic subspecies of the **Prairie Warbler** (*D. discolor paludicola*) (discussed in the species profiles) which here is a subspecies endemic to the mangroves.

Blackbirds and Orioles (Order Passeriformes, Family Emberizidae: Icterinae)

This is a heterogeneous taxon of birds with respect to plumage patterning, size, and social organization. Many species of New World birds belong to this taxon: orioles (troupials), cowbirds, meadowlarks, grackles, blackbirds, etc. Two of the species are discussed in the species profiles (**Appendix B**). The **Bobolink** (*Dolichonyx oryzivorus*), a migrant that passes through the study area, performs one of the longest migrations of land birds. The **Red-winged Blackbird** (*Agelaius phoeniceus*) is a Permanent Resident of our marshes and marsh-bordering areas of the landscape.

Sparrows (Order Passeriformes, Family Emberizidae:Emberizinae)

The Emberizinae is the taxon of the New World finches including towhees, juncos, Snow Buntings, and the many species of streaked sparrows. The **Cape Sable Seaside Sparrow** (*Ammodramus maritimus mirabilis*), an Endangered species (FGFWFC and USFWS), is a Permanent Resident of the study area. The range of this subspecies was formerly restricted to four areas within extreme South Florida. The Cape Sable Seaside Sparrow's range within the cord grass (*Spartina bakeri*) marsh stretched from Flamingo to northwestern Cape Sable and is now unoccupied, or apparently so (Kushlan and Bass 1983) as is the Ochopee-Carnestown range. The remaining areas of its range are inland from the coast: East Everglades, Taylor's Slough, and Big Cypress National Preserve. The remaining population in 1981 was 6,600 birds (Kushlan and Bass 1983). The present inland habitats of this subspecies would seem to render it sufficiently removed from the dangers of floating spills.

CONCLUSIONS

Oil and the Avifauna

More than 150 species of birds known to occur within the study area have been considered in this chapter. These species, by virtue of their habitats and habits, represent differing degrees of vulnerability to oil pollution. Appropriate conditions prevailing, however, any of them can be strongly affected, e.g.:

- **The pelagic species** (shearwaters, petrels, storm-petrels, tropicbirds, boobies, phalaropes, several terns, etc.) that spend their non-nesting months at sea.
- **The very vulnerable coastal and estuarine species that swim submerged for their prey** (loons, grebes, cormorants, anhingas, mergansers, etc.).
- **The many coastal and estuarine species that pluck food from the surface or plunge shallowly for it** (frigatebirds, ospreys, Bald Eagles, gulls, many species of terns, etc.).
- **The surface-swimming birds** (pelicans and the ducks and coots that may grub up food or dive in search of it).

- The long-legged wading birds (herons, egrets, ibises, spoonbills, storks, etc.).
- The widely diversified assemblage of shorebirds that run and forage along sandy beaches and mudflats (plovers and sandpipers).
- The scavengers of the shorelines (vultures, eagles, gulls, crows, etc.).
- The diversified inhabitants of the mangrove forests (rails, pigeons, cuckoos, warblers, etc.).
- The inhabitants of the coastal marshes and prairies and the tropical hammocks and upland growth that border marine ecosystems.

There is a "hard" approach to avifaunal mortality from oil pollution. Some species of marine birds in the far northern oceans occur in the hundreds of thousands and even millions. For these species, mortality has been rationalized as but a small percentage of the total annual mortality. As such, species numbers should not be affected. But South Florida is not the Arctic. Numbers of most species in the study area are much smaller. Many number in but thousands or even hundreds of individuals. Mortality in such populations can be critical indeed.

There is a very special point to be made about extirpating even portions of an avifauna. Hochbaum (1955) helped direct our thinking to the "traditions" of wildlife, especially birds. Destroy a breeding population, a wintering population, or even the population that pauses at certain points in migration, and in succeeding years, no others of the species may come here. There are none now who "know" these surroundings to which they were imprinted. Their traditions have been broken.

Many of the assemblages of birds breeding in the study area are believed to be distinct subpopulations of their species. They have their traditions to these areas and, in addition, they have, assumedly, unique gene pools. They are finely adapted to these particular environments. Such adaptations are not achieved quickly. The white and blue morphs of the **Great Blue Heron** fall into this category, as well as the **Reddish Egret** and the **Roseate Spoonbill.**

Mortality and sublethal effects from oiling in South Florida could have not only local but continent-wide ramifications, with such also being expressed in the West Indies, South America, and distant pelagic areas of the Southern Hemisphere. The avifauna of the study area is variously adapted for pelagic, offshore, inshore littoral, and terrestrial habitats interfacing with coastal marine areas. This is not a sedentary avifauna; it is by no means entirely, or evenly largely, non-migratory. Changes occur seasonally in species diversity and species population densities, as well as intra-population composition. Migrants from Temperate Zone prairies and forests, far western plains and lakes, the Arctic, the Subarctic, as well as the Neotropics, reach South Florida: some to winter; some to summer and nest; and some to pass through the State en route to and from the West Indies, South America, and distant pelagic points. Some pelagic visitors are inter-hemispheric. Young and adults of many nesting species disperse widely after nesting, and dispersers from outside the study area arrive after their nesting.

Contemplation of oil pollution usually envisions accidents at the drilling rig or in transportation, resulting in abrupt release of quantities of oil, producing rapid mortality and habitat degradation. But avifaunal mortality and habitat degradation may occur slowly and just as surely. With oil production under way, oil-tanker traffic will increase. So, too, will spills at the taking on of oil, at flushings of oil tanks, and around all of the

activities involving oil in the environment. Oil tankers may run aground, as several freighters have done recently in the Florida Keys and Dry Tortugas.

It may be difficult for the non-biologist to think of ecosystems and their habitats as irreplaceable. Usually, there is more of the same somewhere else. For example, the Tundra, the Taiga, and the Prairies extend for hundreds of miles of latitude. If portions of these areas are compromised, there is always more. But such thinking does not apply to the study area. There is no other Florida Bay, no other Dry Tortugas, and in the continental U.S., no other mangrove forests or tropical hammocks such as we have in South Florida. If these areas are compromised, they cannot be replaced. They cannot be cleaned, rehabilitated, or mitigated somewhere else. Mangrove muck retains oil for many years, and oiled beaches are slow to cleanse themselves. Once degradation of the habitat begins, the avifauna is compromised.

Harvard University's noted biologist, Thomas Barbour, wrote of Florida as "that vanishing Eden" (Barbour 1944). He described Florida as one of the most extraordinary states in the Union. Florida, he said, proved to be "an easy state for man to ruin" and "he has ruined it with ruthless efficiency." Florida Bay and the Everglades, the Ten Thousand Islands and the Southwest Florida coast, the Dry Tortugas, the Lower Keys wildlife refuges, John Pennekamp Coral Reef State Park, etc.--these are precious remnants of the extraordinary state Florida once was. The growing traffic of oil-laden vessels, the increasing problem of near-empty oil tanks flushed into open waters, and the possibility of spills from oil and gas prospecting offshore South Florida all pose threats to these unique, fragile ecosystems, which are critical to South Florida's avifauna.

Information Needs

The avifauna of South Florida's inshore, littoral, salt marsh, mangrove and marine-interfacing inland habitats is well known in terms of general life-histories and seasonalities of occurrence. What is lacking is information about the pelagic birds which occur offshore. There is also a lack of information about the movements and derivations of some populations, such as wading birds (herons, etc.) and shorebirds (plovers, sandpipers, gulls, terns, etc.).

Each spring, large numbers of **Greater Shearwaters**, **Sooty Shearwaters**, and **Wilson's Storm-Petrels** migrate from breeding areas in the South Atlantic to water masses of the North Atlantic. Substantial numbers of these pelagic species pass offshore South Florida during May to June. How many funnel through the Straits of Florida we can only infer from offshore counts that have been made at points to the north (i.e., offshore coastal southeastern U.S.). Each fall, tundra-bred populations of phalaropes (i.e., the **Red Phalarope** and **Red-necked Phalarope**) pass southward offshore South Florida in migration to pelagic waters of the Southern Hemisphere. The phalaropes collect and linger in Gulf Stream upwellings (Haney 1986b). In fall, **Cory's Shearwaters** reach Florida's Atlantic coastal waters from their breeding areas in the eastern Atlantic; some pass on into the Gulf of Mexico. These are not the only pelagic species frequenting offshore waters of South Florida. In any season, pelagic birds of numerous species may be found, some in migration, some while foraging from nesting grounds outside Florida, some as post-breeding dispersers, and some simply as Casual Visitors. These individuals of mixed species constitute what is known as a pelagic "community" of birds--a term first used by Jespersen (1929) in describing the birds over the "High Atlantic Ocean."

The Gulf of Mexico, including the offshore waters of Southwest Florida, the oceans surrounding the Lower Florida Keys and the Dry Tortugas, and the contiguous waters of Florida Bay, has its community of pelagic birds, the species components changing seasonally. What are the sources of these birds? Not all are sedentary in the Gulf.

The **Northern Gannet** population from Newfoundland migrates south along the Atlantic coast and winters offshore in the Gulf (Nelson 1978). The gannets enter the Gulf through the Straits of Florida, presumably passing between Cay Sal Bank and the Florida Keys. What of the shearwaters, petrels, storm-petrels, jaegers, etc. that enter the Gulf? Do they enter through the Straits of Florida and in what numbers? How many enter through the Straits of Yucatan?

An established procedure for gathering information about birds in the pelagic environment is by oceanic transects. From the context of needed knowledge as expressed in the preceding paragraphs, such transects should pass between (1) Key Largo and the Great Bahama Bank; and (2) the Lower Keys to Cay Sal Bank and then to Cuban territorial waters. A not mandatory, but useful, transect would be one laid out to census the pelagic birds joining the Gulf Stream via the Northwest Providence Channel. The data would not concern the study area, but might indeed indicate that fewer birds than now suspected pass through the Straits of Florida. If the transects were run often enough, back and forth at least once a week for a year, and if they were adequately manned with qualified personnel, an enormous amount of information would be gathered. Such information has been gathered offshore North Carolina coastal areas (Lee 1986), and offshore the Central Florida Gulf coast by a few sporadic trips (Buhrman and Hopkins 1978); these studies have been abundantly quoted and stand as important, and they are, but they represent an entirely inadequate series of samples.

Perhaps Cuban ornithologists could participate in transects from Cay Sal Bank to the Cuban coast, and supply information regarding pelagic birds nesting on islets of Cuba's north coast. This would increase our appreciation of the origin of some of the study area's pelagic birds.

Certain pelagic species (i.e., **Audubon's Shearwater**) and near-pelagic ones (i.e., **Bridled Tern**) which do not nest in Florida occur in offshore and even inshore waters of the study area throughout the year. Many of these must come from nearby nesting colonies of these birds. On the extensive Cay Sal Bank, <100 km (54 nmi) south of the Upper Keys, are numerous cays (islands) and rocks (e.g., Anguilla Cays, Cay Sal, Damas Cays, Double Headed Shot Cays, Dog Rocks, and Elbow Cay). Various cays and rocks lie south of Bimini in the western Bahamas Islands. Most of these probably are used for nesting by **Audubon Shearwaters, Bridled Terns, Brown Noddies,** and others. Modern censuses of breeding seabirds on these islands, particularly those of Cay Sal Bank, are required in order to fully document populations of these birds that forage near and within the study area. This information will also be important in understanding the magnitude of the problem to be faced should oil spills from prospecting areas or from ship traffic spread to these nearby areas.

For the information of petroleum-oriented interests, it is suggested that a summary of seabird breeding islets, rocks, pinnacles, etc. for the Straits of Florida, including the area from western Cuba, the Dry Tortugas, Cay Sal Bank, the Great Bahama Bank, and Andros Island through the Little Bahamas Bank be published. This would be useful to the industry and to biologists, much as is the *Florida Atlas of Breeding Sites for Herons and their Allies: 1976-1978* (Nesbitt et al. 1982).

The wading birds (herons, egrets, ibises, storks, etc.) are an outstanding avian feature of South Florida and the study area. One of the most important gaps in information is with respect to the "derivation" of the populations of these species. More than a dozen of these breed in South Florida. To what extent are these birds sedentary? To what extent have they migrated into the area to breed; and if so, from where? Wading birds are characterized by post-breeding dispersals. To what areas do our post-breeding birds disperse? In fall, populations of many species move into South Florida. Where have they come from? To what extent do they winter here? To what

extent do they move on and, if so, where do they winter? Where do the spring migrants come from? Where are they going? Dispersion and movements of the wading bird species present in South Florida is a highly important subject. This knowledge is necessary if we are to appreciate and manage this important avifaunal resource. In the event of mortality of wading birds, what populations are at that season present?

Banding techniques utilizing both USFWS bands and color bands, for quick field recognition, are a standard approach to understanding movements of birds. The movements of the **Gray Heron** (*Ardea cinerea*) of Eurasia and Africa are known in surprising detail (Rydzewski 1956). The same detailed information should be available for North American ciconiids. Byrd (1978) made much progress with several species. Ryder (1978) contributed information regarding the **Snowy Egret**. There has been banding and marking of South Florida birds. But this is needed on a large scale. The localities of the nesting colonies of the study area's herons are sufficiently well-known that banding of these birds could be accomplished in significant numbers. Where do our birds disperse and/or migrate to? Nesting colonies of the southeastern U.S. birds are also rather well-known. Wide-scale banding of these birds will supply information as to derivation of dispersers and migrants into the study area. Large-scale mortality of South Florida birds can then be extrapolated to consideration of effects on the populations present at that time. These populations, it is important to point out, may well be genetically distinct, and, as such, have unique physiologies, geographical and habitat orientations, and "traditions."

There is expanding interest and research effort with migratory patterns and winter habitat use of shorebirds (plovers, sandpipers, etc.). Individuals of many species winter on beaches of South Florida within the study area. Many more pause on these beaches during their long-distance migrations. Work such as that being carried out by Theodore Below, a National Audubon Society Research Warden stationed at Rookery Bay, should be expanded (see Below 1989a,b). We need to know much more about the local wintering populations and their movements and about the numbers that pause along our beaches in migration. Few birds are more directly threatened by oil spills than these birds that spend their non-breeding months on marine beaches and tidal flats.

Finally, there exists a major information gap that hampers evaluation of the importance of the local avifauna. Little information is available as to the total numbers of most North American species of birds. Clapp (1989) attempted to estimate populations of marine birds of the continent. There are few, if any, estimates for wading bird populations, shorebird populations, raptor populations, etc. of the continent. Beginnings have been made in censusing regional populations of some species. Portnoy et al. (1981) prepared an atlas of coastal colonies of gulls, terns, pelicans, cormorants, and skimmer colonies from North Carolina to Key West. Seven regional investigators and numbers of other contributors gathered the information for this effort. The data are relatively old now (1976); the survey should be brought up to date and should be attempted over a much wider area. Eventually we could achieve, at least for the populations of larger birds and colonial breeding ones, what has been achieved for waterfowl populations (Bellrose 1980). For many years, however, we have had surprisingly realistic estimates of waterfowl populations (Bellrose 1980). If such information were available for at least some other taxa, we could better assess importance of local populations in the context of larger geographical areas. We could also better appreciate the significance of the numbers of wading birds and species of marine birds migrating through the study area and wintering there. Obtaining such information might not be of extraordinary difficulty. Local organizations of capable amateur and professional observers span the continent. The USFWS unit of Flyway Biologists is a census-trained organization that produces yearly determinations of waterfowl numbers (Hawkins et al. 1984). To this writer, it would seem that the larger wading birds could be censused continent-wide.

REFERENCES CITED

Adams, C. A., J. Oesterling, S. C. Snedaker, and W. Seaman. 1973. Quantitative dietary analysis for selected dominant fishes of the Ten Thousand Islands, Florida. In *The role of mangrove forest ecosystems in the maintenance of environmental quality and high productivity of desirable fishes*, ed. S. E. Snedaker and A. Lugo, H1-H56. Washington, DC: Bureau of Sport Fisheries and Wildlife.

American Ornithologists' Union. 1983. *Check-list of North American birds, 6th Ed.* Lawrence: Allen Press, Inc.

Ashmole, N. P. 1968. Body size, prey size, and ecological segregation in five sympatric tropical terns (Aves: Laridae). *Syst. Zool.* 17:292-304.

Ashmole, N. P. 1971. Sea bird ecology and the marine environment. In *Avian Biology, Vol. 1*, ed. D. S. Farmer and J. R. King, 223-286. New York: Academic Press.

Audubon, J. J. 1831-1839. *An ornithological biography, Vols. 1 to 5*. Philadelphia: E. L. Cary, Vol. 1; A. and C. Black, Vols. 2 to 5.

Barber, R. D., and J. B. Johnson. 1976. An offshore sighting of Sabine's Gulls. *Fla. Field Natur.* 4:14.

Barbour, T. 1944. *That vanishing Eden.* Boston: Little, Brown, and Co.

Bellrose, F. C. 1980. *Ducks, geese and swans of North America.* Harrisburg: Stackpole Books.

Below, T. 1989a. *Progress report Cape Romano shorebird banding.* Report prepared for National Audubon Society, Rookery Bay Sanctuary. Naples.

Below, T. 1989b. *Report of colonial nesting, Southwest Florida, 1989.* Report prepared for National Audubon Society, Rookery Bay Sanctuary. Naples.

Bourne, W. R. P. B. 1970. Special review - after the 'Torrey Canyon' disaster. *Ibis* 112:120-125.

Bowman, R., and G. T. Bancroft. 1989. Least Bittern nesting on mangrove keys in Florida Bay. *Fla. Field Natur.* 17:43-46.

Buckley, P. A. 1973. A massive spring movement including three species new to North Carolina, at Cape Hatteras National Seashore. *Am. Birds* 27:8-10.

Buhrman, C. B., and L. A. Hopkins. 1978. Eleven pelagic trips into the eastern Gulf of Mexico. *Fla. Field Natur.* 6:30-32.

Burger, J. 1984. Shorebirds as marine animals. In *Shorebirds, breeding behavior and populations, behavior of marine animals, Vol. 5*, ed. J. Burger and B. L. Olla, 17-81. New York: Plenum Press.

Burger, J. 1988. Foraging behavior in gulls: Differences in method, prey and habitat. *Colonial Waterbirds* 11:9-23.

Byrd, M. A. 1978. Dispersal and movements of six North American Ciconiiformes. In *Wading birds*, ed. A. Sprunt IV, J. C. Ogden, and S. Winckler, 161-185. New York: National Audubon Society Research Rep. 7.

Chan, E. T. 1977. Oil pollution and tropical littoral communities. In *Biological effects of the 1975 Florida Keys oil spill.* 1977 Oil Spill Conference, 539-542. Washington, DC: American Petroleum Institute.

Clapp, R. B. 1989. Status trends in populations of marine birds of North America. Abstract of paper presented to Colonial Waterbird Society Annual Meeting, Oct. 26-29, Key Largo, FL. (Abstract 31).

Clapp, R. B., and W. B. Robertson, Jr. 1986. Nesting of the Masked Booby on the Dry Tortugas: The first record for the contiguous United States. *Colonial Waterbirds* 9:113-116.

Clapp, R. B., R. C. Banks, D. Morgan-Jacobs, and W. A. Hoffman. 1982. *Marine birds of the southeastern United States and Gulf of Mexico. Pt. I. Gaviiformes through Pelecaniformes.* FWS/OBS-82/01. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Clapp, R. B., D. Morgan-Jacobs, and R. C. Banks. 1983. *Marine birds of the southeastern United States and Gulf of Mexico. Pt. III. Charadriiformes.* FWS/OBS-83/30. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Clark, R. B. 1984. Impact of oil pollution on seabirds. *Environ. Pollut.* 33:1-22.

Collie, M. R. 1978. A Sabine's Gull at the Dry Tortugas, Florida. *Fla. Field Natur.* 7:28.

Cramp, S., K. E. L. Simmons, R. Gillmor, P. A. D. Hollom, R. Hudson, E. M. Nicholson, M. A. Ogilvie, P. J. S. Olney, C. S. Roselaar, K. H. Voous, D. I. M. Wallace, and J. Wattel, ed. 1980. *Handbook of the birds of Europe, the Middle East and North Africa. Vol. 2.* Oxford: Oxford Univ. Press.

Cramp, S., K. E. L. Simmons, D. J. Brooks, N. J. Collar, E. Dunn, R. Gillmor, P. A. D. Hollom, R. Hudson, E. M. Nicholson, M. A. Ogilvie, P. J. S. Olney, C. S. Roselaar, K. H. Voous, D. I. M. Wallace, J. Wattel, and M.G. Wilson, ed. 1983. *Handbook of the birds of Europe, the Middle East and North Africa. Vol. 3.* Oxford: Oxford Univ. Press.

Cramp, S., D. J. Brooks, E. Dunn, R. Gillmor, P. A. D. Hollom, R. Hudson, E. M. Nicholson, M. A. Ogilvie, P. J. S. Olney, C. S. Roselaar, K. E. L. Simmons, K. H. Voous, D. I. M. Wallace, J. Wattel, and M.G. Wilson, ed. 1985. *Handbook of the birds of Europe, the Middle East and North Africa. Vol. 4.* Oxford: Oxford Univ. Press.

Davis, J. H., Jr. 1942. *The ecology of the vegetation and topography of the Sand Keys of Florida.* Papers from the Tortugas laboratory. Vol. 33.

Dinsmore, J. J. 1972. Sooty Tern behavior. *Bull. Fla. State Mus. (Biol. Sci.)* 16:129-179.

Florida Game and Fresh Water Fish Commission. 1989. *Official list of Endangered and potentially Endangered flora and fauna in Florida.* Tallahassee: Florida Game and Fresh Water Fish Commission.

Ford, R. G., G. W. Page, and H. R. Carter. 1987. Estimating mortality of seabirds from oil spills. In *Proceedings, 1987 Oil Spill Conference*, 547-551. Washington, DC: American Petroleum Institute.

Frederick, P. C., and M. W. Collopy. 1988. *Reproductive ecology of wading birds in relation to water conditions in the Florida Everglades.* Florida Cooperative Fish and Wildlife Research Unit, School for Research and Conservation, Univ. of Florida Tech. Rep. No. 30.

Fritts, T. H., A. B. Irvine, R. D. Jennings, L. A. Collum, W. Hoffman, and M. A. McGehee. 1983. *Turtles, birds and mammals in the northern Gulf of Mexico and nearby Atlantic waters.* FWS/OBS-82/65. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Greenway, J. C., Jr. 1967. *Extinct and vanishing birds of the world, 2nd Rev. Ed.* New York: Dover Publ., Inc.

Gusey, W. P. 1981. *The fish and wildlife off the South Atlantic coast.* Houston: Shell Oil Co.

Haney, J. C. 1986a. Seabird affinities for Gulf Stream frontal eddies: Responses of mobile marine consumers to episodic upwelling. *J. Mar. Res.* 44:361-384.

Haney, J. C. 1986b. Remote sensing of seabird environments. *Am. Birds* 40:396-400.

Haney, J. C., and P. A. McGillivary. 1985. Aggregations of Cory's Shearwaters (*Calonectris diomedea*) at Gulf Stream fronts. *Wilson Bull.* 97:191-200.
Hawkins, A. S., R. C. Hanson, H. K. Nelson, and H. M. Reeves, ed. 1984. *Flyways: Pioneering waterfowl management in North America.* Washington, DC: U.S. Government Printing Office.
Heald, E. J., W. E. Odum, and D. C. Tabb. 1974. Mangroves in the estuarine food chain. In *Environments in South Florida present and past*, ed. P. J. Gleason, 182-189. Miami: Miami Geol. Soc. Mem. No. 2.
Hochbaum, A. 1955. *Travels and traditions of waterfowl.* Minneapolis: Univ. of Minnesota Press.
Howell, A. H. 1932. *Florida bird life.* New York: Coward-McCann, Inc.
Hunt, G. L., Jr. 1987. Offshore oil development and seabirds: The present status of knowledge and long-term research needs. In *Long-term environmental effects of offshore oil and gas development*, ed. D. F. Boesch and N. R. Rabalais, Ch. 2. London: Elsevier Applied Science.
Jespersen, P. 1929. On the frequency of birds over the High Atlantic Ocean. Verh. VI, Int. Ornith. Kongr., Kopenhagen 1926:163-172.
King, J. G., and G. A. Sanger. 1979. Oil vulnerability index for marine oriented birds. In *Conservation of marine birds of northern North America, wildlife research report 11*, ed. J. C. Bartonek and D. N. Nettleship, 227-239. Washington, DC: U.S. Department of the Interior.
Kushlan, J. A. 1981. Resource use strategies of wading birds. *Wilson Bull.* 93:145-163.
Kushlan, J. A., and O. L. Bass, Jr. 1983. Habitat use and the distribution of the Cape Sable Sparrow. In *The Seaside Sparrow, its biology and management*, 139-146. N. C. Biol. Survey and N. C. State Museum.
Kushlan, J. A., and P. C. Frohring. 1986. The history of the southern Florida Wood Stork population. *Wilson Bull.* 98:368-386.
Kushlan, J. A., and D. A. White. 1977. Nesting wading bird populations in southern Florida. *Fla. Sci.* 40:65-72.
Kushlan, J. A., O. L. Bass, Jr., and L. C. McEwan. 1982. Wintering waterfowl in the Everglades estuaries. *Am. Birds* 36:815-819.
Lee, D. S. 1986. Seasonal distribution of marine birds in North Carolina waters 1975-1986. *Am. Birds* 40:409-412.
Matthiessen, P. 1973. *The wind birds.* New York: Viking Press.
Merriam, D. F. 1987. Overview of the geology of Florida Bay, review of recent developments. In *A symposium on Florida Bay, a subtropical lagoon, Program and Abstracts*, 13-14.
Nelson, J. B. 1978. *The Sulidae.* Oxford: Oxford Univ. Press.
Nesbitt, S. A., J. C. Ogden, H. W. Kale II, B. Patty, and L. A. Rowse. 1982. *Florida atlas of breeding sites for herons and their allies: 1976-1978.* U.S. Department of the Interior, U.S. Fish and Wildlife Service.
Odum, W. E., and R. E. Johannes. 1975. The response of mangroves to man-induced environmental stress. In *Tropical marine pollution*, ed. E. J. Ferguson Wood and R. E. Johannes, Ch. 3. Amsterdam: Elsevier Scientific Publ. Co.
Ogden, J. C. 1985. The Wood Stork. In *Audubon wildlife report 1985*, ed. R. L. Di Silvestro, 458-470. New York: National Audubon Society.
Owre, O. T. 1967. Adaptations for locomotion and feeding in the Anhinga and the Double-crested Cormorant. *Am. Ornithol. Union Monogr.* 6:138.
Owre, O. T. 1978. White-crowned Pigeon. In *Rare and Endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 43-45. Gainesville: Univ. Presses of Florida.
Page, G., and D. F. Whitacre. 1975. Raptor predation on wintering shorebirds. *Condor* 77:73-83.
Palmer, R. S. 1962. *Handbook of North American birds. Vol. 1.* New Haven: Yale Univ. Press.
Pearson, T. G. 1937. *Adventures in bird protection.* New York: Appleton-Century Co.
Peterson, R. T. 1984. Introduction. In *The herons handbook*, ed. J. Hancock and J. A. Kushlan, Vol. 7. New York: Harper & Row.
Portnoy, J. W., R. M. Erwin, and T. W. Custer. 1981. *Atlas of gull and tern colonies: North Carolina to Key West, Florida (including pelicans, cormorants and skimmers).* FWS/OBS-80-05. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.
Powell, G. V. N. 1987. Habitat used by wading birds in a subtropical estuary: Implications of hydrography. *Auk* 104:740-749.
Powell, G. V. N., R. Bjork, J. C. Ogden, R. T. Paul, A. H. Powell, and W. B. Robertson. 1982. An analysis of population trends in some Florida Bay wading birds. In *A symposium on Florida Bay, a subtropical lagoon, Program and Abstracts*, 19-20.
Powell, G. V. N., R. D. Bjork, J. C. Ogden, R. T. Paul, A. H. Powell, and W. B. Robertson, Jr. 1989. Population trends in some Florida Bay Wading Birds. *Wilson Bull.* 101:436-437.
Puttick, G. M. 1984. Foraging and activity patterns in wintering shorebirds. In *Shorebirds, migration and foraging behavior, behavior of marine animals, Vol. 6, Ch. 4*, ed. J. Burger and B. L. Olla, 203-231. New York: Plenum Press.
Reed, N. P., and D. Drabelle. 1984. *The United States Fish and Wildlife Service.* Boulder: Westview Press.
Robblee, M. B., and J. T. Tilmant. 1987. Distribution, abundance, and recruitment of the pink shrimp (*Penaeus duorarum*) within Florida Bay. In *A symposium on Florida Bay, a subtropical lagoon, Program and Abstracts*, 20.
Robertson, W. B., Jr. 1978. Sooty Tern. In *Rare and Endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 89-91. Gainesville: Univ. Presses of Florida.
Robertson, W. B., Jr., and J. A. Kushlan. 1974. The southern Florida avifauna. In *Environments of South Florida: Present and past*, ed. P. J. Gleason, 414-452. Miami: Miami Geol. Soc. Mem. No. 2.
Robertson, W. B., Jr., and C. R. Mason. 1965. Additional bird records from the Dry Tortugas. *Fla. Natur.* 38:131-138.
Ryder, R. A. 1978. Breeding distribution, movements, and mortality of Snowy Egrets in North America. In *Wading birds*, ed. A. Sprunt IV, J. C. Ogden, and S. Winckler, 197-205. New York: National Audubon Society.
Rydzewski, W. 1956. The nomadic movements and migrations of the European Common Heron *Ardea cinerea* L. *Ardea* 44:71-188.
Schomer, N. S., and R. D. Drew. 1982. *An ecological characterization of the lower Everglades, Florida Bay, and the Florida Keys.* FWS/OBS-82/58. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Senner, S. E., and M. A. Howe. 1984. Conservation of Nearctic shorebirds. In *Shorebirds, breeding behavior and populations, behavior of marine animals, Vol. 5*, ed. J. Burger and B.C. Olla, 379-421. New York: Plenum Press.

Sykes, P. W., Jr., H. P. Langridge, and T. Trotsky. 1984. Sight record of Band-rumped Storm Petrel off the coast of Palm Beach County, Florida. *Fla. Field Natur.* 12:17-18.

Taylor, J. W. 1972. Probable Bulwer's Petrel of Key West. *Wilson Bull.* 84:198.

Teas, H. J., A. H. Lasday, E. Luque I, R. A. Morales, M. E. De Diego, and J. M. Baker. 1989. Mangrove restoration after the 1986 Refineria Panama oil spill. Proceedings of the 1989 Oil Spill Conference. *Am. Pet. Inst. Publ.* 4479:587.

Tebeau, C. W. 1957. *Florida's last frontier: The history of Collier County*. Miami: Univ. of Miami Press.

Terres, J. K. 1980. *The Audubon Society encyclopedia of North American birds*. New York: Alfred A. Knopf.

Wallace, G. J., and H. D. Mahan. 1975. *An introduction to ornithology, 3rd Ed.* New York: MacMillan Publ. Co., Inc.

Watson, G. 1966. *Seabirds of the tropical Atlantic Ocean*. Washington, DC: Smithsonian Press.

Wiley, J. W., and B. N. Wiley. 1979. The biology of the White-crowned Pigeon. *Wildl. Monogr.* 64:1-54.

Williams, L. E., Jr. 1965. Jaegers in the Gulf of Mexico. *Auk* 82:19-25.

Woodcock, A. H. 1940. Observations on Herring Gull soaring. *Auk* 57:219-224.

Woolfenden, G. E., and W. B. Robertson, Jr. 1974. Least Terns nest at Dry Tortugas. *Fla. Field Natur.* 2:19-20.

Yokel, B. 1983. Animal abundance and distribution in Rookery Bay Sanctuary, Collier County, Florida. Ph.D. diss., Univ. of Miami.

CHAPTER 10
SUBMERGED CULTURAL RESOURCES

Contributions by Timelines, Inc. and Carl J. Clausen

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INTRODUCTION

Like archeology performed on land, the preservation and study of submerged cultural resources affects our understanding of our origins and past history. Such remains serve as visible reminders of the human past and provide information that is essential to our knowledge of how people lived in earlier times. Information from submerged archeological sites illuminates the antiquity of Native American cultures in the New World and their adaptation to changing environmental and social conditions. Similar understanding is available through the preservation and study of material remains of Colonial and later periods in New World history.

With the advent of improved technologies for underwater exploration, there has arisen a corresponding need for preservation and study of submerged cultural remains. In the case of shipwrecks and other material remains from historic times in the New World, we often find that underwater studies provide ideas about how life was lived in the past that are not available through historic documents or that, indeed, may differ from those found in documentary accounts. It is now clear to archeologists that the preservation and study of submerged cultural resources is essential to our understanding of both the historic and prehistoric past in the New World.

But *are* there cultural resources on the outer continental shelf (OCS) of South Florida? If there are, what integrity do they have? Can one identify them with current techniques? And finally, can they be recovered, once found? The answers to these questions are key elements in the cultural resource management program of the Minerals Management Service (MMS). In answering these questions, we will make use of the following definitions (taken from MMS 1986):

- **Detectability** is the potential for state-of-the-art technology to locate the resource. Factors pertinent to detection include the size and composition of the resource; the water depth and/or depth of burial of the resource; and the survey line spacing, instrument type, and instrument sensitivity necessary to locate the resource.

- **Habitability** is the potential for a location to have been occupied by prehistoric human populations. Factors contributing to habitability are sea level changes and the existence of relict Pleistocene or Holocene landforms.

- **Recoverability** is the ability to collect archeological resource information using current technology based on the depth of burial and/or the depth of water of the potential resources.

- **Survivability** is an assessment of the effects of physical forces or processes such as glacial scouring, sea ice gouging, subaerial exposure, inlet migration, transgressive seas, and sedimentation on a potential archeological resource.

An additional feature of this chapter is that it recognizes as essential to the management of the shelf's archeological resources the archeological contexts, research topics, and preservation priorities developed in *Florida's Comprehensive Historic Preservation Plan* (Florida Department of State, Division of Historical Resources in prep.) as a framework for presenting the cultural history and management issues of the relevant archeological periods for the study area. These contexts, research topics, and preservation priorities will be essential tools for management when resources are encountered in the study area and their significance must be evaluated.

This chapter addresses cultural resources expected to exist on the shelf, which fall into two categories: (1) remains of prehistoric land use, and (2) remains of vessels lost over the last several thousand years. The first section discusses the expected nature and distribution of drowned prehistoric resources--those archeological sites which, due to sea level rise over the last 12 millennia, have been covered by the sea and its accompanying transgressive sand sheet. This process is expected to have protected some sites intact, while modifying or destroying others. Storms and currents are also expected to have played a role in protecting or damaging these resources. Our current understanding of the exact effects of these processes on the cultural resources of the South Florida shelf is limited and additional directed studies will be critical for increasing our ability to predict accurately the nature and distribution of drowned prehistoric cultural resources.

The second part of this chapter discusses those vessels that have been lost on the shelf and whose remains can be expected to survive. Such vessels include historic period as well as aboriginal canoes used for trade, fishing, transportation, etc. before the arrival of European sailing ships. The analysis of lost vessels includes discussions of factors affecting vessel loss, the preservation of these vessels within the South Florida offshore environment, and predictive modeling for their distribution.

A third section of this chapter discusses current issues in the management of cultural resources. Included are issues raised by the State of Florida and issues relating to cultural resources beyond State-controlled waters. The final section presents a summary of findings, a discussion of data gaps, and recommendations for additional studies that will help fill these gaps.

DROWNED PREHISTORIC RESOURCES

Archeological Contexts

The prehistory of South Florida is best known for the most recent 4,000 years, that is, the time divisions systematized in the Late Archaic (Pre-Glades) and Glades sequence (see the recent reviews of Griffin 1988, 1989; Widmer 1988). Although encompassing important sites and cultural developments, notably the adaptive processes that resulted in the development of complex societies founded on hunting and gathering (a fairly rare phenomenon in world prehistory), these cultures are not directly pertinent to the current study because none of this archeological record, with the exception of sunken aboriginal boats, is likely to be located on the continental shelf; the exception to this generalization will be considered in the section entitled Lost Vessels.

By contrast, the eight millennia of South Florida's prehistory prior to 4,000 years before present (4000 BP) are relatively poorly known, in large measure because most of the archeological evidence for this long period now lies beneath the sea.

Paleoindian

Human communities seem first to have entered South Florida around 12,000 BP. This date reflects local empirical knowledge, based on the tortoise kill at Little Salt Spring (Clausen et al. 1979), and slightly later (about 10,000 to 9000 BP) by occupation at this same site and at Warm Mineral Springs (Clausen et al. 1975) in Sarasota County and at the Cutler Fossil Site (Carr 1986) in Dade County. These Paleoindian localities and the Clovis and Dalton horizons to which they belong are not necessarily the earliest possible in South Florida or elsewhere in the Americas. Their ultimate status depends on resolution of the ongoing "pre-Clovis" controversy and the date of human colonization of North America (see Meltzer 1989 and literature cited there). The current study assumes a terminal Pleistocene date for human colonization of the

Americas, and takes 13,000 to 12,000 BP as the theoretically as well as empirically earliest date of human occupation in South Florida, even while recognizing that this position may be overturned by future research.

Archaic

The Early Archaic period (roughly 9000 to 7000 BP) is not certainly known to be represented in South Florida, and some commentators have suggested that the region was abandoned at this time (e.g., Widmer 1988). Such an extreme position is not warranted, particularly since the scarcity of locally occurring outcrops of lithic raw materials implies the importance of nonlithic tool kits in South Florida. In any case, this issue is an important one, particularly for zones of potential settlement now lying beneath the sea.

Occupation becomes far more evident in the succeeding Middle Archaic period (7000 to 4000 BP), when large habitation and mortuary sites become relatively frequent; the Little Salt Spring (Clausen et al. 1979), Bay West (Beriault et al. 1981), and Windover (cf. Doran 1988) sites may be singled out as important localities recently investigated. At the same time, the pre-ceramic components at the bottoms of a few shell middens on the Southwest Florida coast belong to this period (reviewed in Griffin 1988), marking the approach of the paleoshoreline and the end of possible human occupation of zones now offshore.

Habitability

In order to evaluate the potential of the continental shelf for containing prehistoric resources, it is first essential to determine the potential of the subaereal (exposed) continental shelf for attracting humans and thus harboring remains of their activities. We use the term "habitability" to describe this potential. This summary review of trends in South Florida prehistory indicates that there were eight millennia of human occupation of the area at times when sea levels were lower than they are at present. Lower sea levels offered expanses of exposed continental shelf for human exploitation and location of settlements. Recent investigations in this subtidal zone elsewhere off the Florida Gulf coast have revealed traces of exactly this kind of human activity (presented in the next section), and analogous evidence surely exists in the waters off the South Florida coast. The purpose of the present section of this chapter is to review the environmental forces that structured human activity in earlier prehistoric times and to evaluate the probable distributions of submerged archeological sites.

Sea Levels

At the global scale, relative sea levels responded to glacial cycles, where sea levels drop as global water is tied up in continental ice sheets during colder episodes, and then rise again as water is released by global warming. In different regions, this simple model is greatly complicated by crustal movements in response to loading and unloading of ice sheets, marine water, and sedimentation and to tectonic events. This complexity of local and regional factors means that local marine regression-transgression cycles must be judged on the strength of *local* geomorphological evidence. Various models at the global scale suggest that the most recent regression-transgression cycle was greater than 100 m in amplitude, that is, that sea levels were at least 100 m below the present level at about 18,000 BP, with progressively rising levels during the terminal Late Pleistocene and earlier Holocene as global temperatures increased. This model also presents a complex transgressive process, with minor transgression-regression fluctuations on the order of 1 to 3 m during the past 7,000 years (see for example Milliman and Emery 1968; Lind 1969; Morner 1976; Fairbridge 1984).

While several recent models of early human occupation of South Florida rely on these global models, particularly with respect to amplitude of the most recent transgression (e.g., Widmer 1988), such models seem inappropriate for this region. Dated in-place features off the Atlantic coast of the southeastern U.S. imply a much shallower relative low sea stand at the end of the Pleistocene, with sea levels of -35 m at 12,000 BP, when human occupation is first documented in Florida (Blackwelder et al. 1979). In South Florida itself, dated peat deposits in the Florida Keys indicate a relative sea level of -15 m at this same date (Scholl et al. 1969; Robbin 1984; Shinn et al. 1989). Both of these new transgression curves imply paleoshorelines much closer to the modern littoral, and slower vertical and horizontal rates of transgression than those that would be obtained by application of global models to South Florida.

The new transgression curve also better collates the available archeological and paleontological indications of prior occupation of the continental shelf in the eastern Gulf of Mexico. Drowned offshore archeological sites exist in up to 12 m of water, most notably at Ray Hole Spring where the local transgression is fixed by radiocarbon dates of roughly 8,200 BP on a sample of live oak and of roughly 7,400 BP on oyster shell (Anuskiewicz 1988a,b). This pair of dates brackets the local transgressive event, placing it in the early to mid eighth millennium BP; the timing and depth of this event would place it on the curve proposed by Blackwelder et al. (1979). A commercial exploration for the Spanish galleons *Nuestra Senora de Atocha* and *Santa Margarita* off the Marquesas Keys located a thick peat formation under 5 to 6 m of eolian and/or waterborne sediments and in nearly 8 m of water. The peat contained various macroorganics, including mammoth or mastodon bone (D. Mathewson, pers. comm. 1979 to C. Clausen). Because proboscideans became extinct in North America by about 10,500 BP (Meltzer and Mead 1985), these bones provide a *terminus ante quem* for the peat deposit. This paleontological information does not precisely date a paleoshoreline position, which Mathewson believes to have been several meters lower than the peat formation, or on the order of 15 m below the modern position. But the locality does affirm a relatively shallow post-Pleistocene transgression and the existence of intact terminal Pleistocene deposits on the continental shelf.

Other drowned archeological sites in the region lie in up to 6 m of water, with cultural materials ranging from Paleoindian to Glades period in date (reviewed in Stright 1988; cf. Faught 1988a,b); most of these localities, especially the older ones, probably do not reflect paleoshoreline occupation, but rather the use of interior regions during the Holocene prior to about 5000 BP. Thus, while it cannot be used to confirm transgression rates and positions of paleoshorelines, the recovery of materials from these archeological localities does demonstrate the existence of prehistoric cultural resources on the continental shelf, now under the sea.

The fundamental implication of these Holocene sea level data for modeling prehistoric site locations may be simply put: archeological sites will not occur in waters more than 45 to 50 m deep because these bathymetric zones were already covered by seawater when humans first entered South Florida at about 12,000 BP. This evaluation of sea level during the Paleoindian period is a conservative one, because much of the evidence reviewed above points to a -15 m level at 12,000 BP, at least in the area of the Florida Keys. The higher figure should be used until this fundamental research question is clarified and resolved. The conservative figure used here approximates the present consensus, especially in archeological circles (e.g., Coastal Environments, Inc. 1982; Daniel and Wisenbaker 1987; MMS 1990). The slower rates of transgression entailed by the new curve also bear consequences for the post-depositional disturbance and integrity of sites and for the physical conditions to which prehistoric human communities were adapted. The implications of this revised model for human paleoecology will be addressed in the next section.

Human Paleoecology

The Holocene marine transgression represents a fundamental natural process in prehistoric occupation in South Florida, because of the surficial geological and hydrological conditions of the region. In its modern condition, South Florida is dominated by the extensive water table drainage provinces represented by the Everglades and Big Cypress Swamp. These large hydrological provinces are recharged by local precipitation, which is provided by the abundant and seasonal rainfall of a tropical savannah regime. The level of this groundwater is controlled, grossly speaking, by the regional climate in conjunction with the hydrostatic forces of sea level. These two controlling factors are not independent. Because much of the moisture released as rainfall finds its origin in the high evapotranspiration rates of regional surface water, the perpetuation of the current hydrological system requires the existence of this surface water. The modern high relative sea levels satisfy this requirement by maintaining a high water table; in the past, however, lower sea levels did not satisfy this requirement.

Lake Okeechobee was formed around 6000 BP, and deposition of peat in the Everglades began around 5000 BP (Gleason et al. 1984). Prior to this time, both sea levels and water-table levels were lower. Little Salt Spring and Warm Mineral Springs provide evidence for levels of water table at several times during the terminal Pleistocene and early Holocene (for example, -26 m at 13,500 BP, -11 to -12 m at 11,000 to 10,000 BP, and -9.5 to -13 m at 10,000 to 9000 BP) (Clausen et al. 1975, 1979). Under these circumstances, surface water was unavailable in the district now occupied by the Everglades, and hydrological regimes analogous to modern patterns were shifted seaward. The biotic communities associated with the modern hydrological conditions were also shifted seaward, and the interior of the peninsula presented an arid, desert-like landscape that lacks a modern analog. Even the biotic communities that approximated modern ones existed under very different conditions. Because less surface water was available to evapotranspiration and resulting precipitation, and because a lower volume of surface runoff entailed smaller amounts of transported terrigenous nutrients, the glades-like and coastal communities were smaller in extent and in biomass available to human exploitation.

This connection between sea levels, surface water, climatic regime, and biotic communities is reflected in the pollen sequence from the nearest studied area, Lake Annie (Watts 1975, 1980), which is supplemented by the pollen data from Warm Mineral Springs (Clausen et al. 1975; Sheldon and Cameron 1976) and Little Salt Spring (Clausen et al. 1979) in Sarasota County. These sources indicate a terminal Pleistocene aridity in South Florida, marked by a low water table and treeless floral communities. During the Early Holocene, this plant cover was replaced by still xeric communities of oak scrub, composites, grasses and some pine. The bleakness of this landscape was ameliorated by more mesic communities around springs: some temperate hardwoods existed around Warm Mineral Springs and Little Salt Spring. These conditions were progressively altered through the earlier part of the Holocene by marine transgression, which laterally shifted coastal communities, near coastal freshwater basins, and the mesic oases of surface water in karstic topography toward the interior until the formation of Lake Okeechobee set in motion the genesis of the modern landscape.

The nature and distribution of modern ecosystems suggests that three systems were of particular importance to prehistoric foraging communities: mangroves, marine tropical meadows, and zones of tidal flow and/or rich current drainage (Widmer 1988). By contrast, high-energy shores and interior zones were far less productive and offered less inducement to human exploitation and settlement. (See **Chapter 4** for presentation of these ecosystems in the modern landscape). On the basis of the implications of optimal foraging theory, Widmer models more recent aboriginal occupation in Southwest Florida

as strongly oriented to the coastal resources contained in large areas of mangrove and tropical meadows; the richness of these coastal zones, especially in the areas of Charlotte Harbor to San Carlos Bay and of the northern section of the Ten Thousand Islands, made possible evolution of the Calusa as a complex society based on hunting and gathering. This prediction of prehistoric population and settlement location is confirmed by the results of Griffin's recent synthesis of Everglades prehistory (Griffin 1988). Griffin shows that during the Glades periods, site locations were distributed in roughly equal proportions between coastal and interior settings, i.e., that both kinds of settings were effectively integrated within a subsistence system. At the same time, populations (measured by the sizes of sites) were far denser on the coast, with 92% of aggregate site area found in coastal mangroves. Thus, although people were present in the interior as well, the aggregate bulk of the population was coastal.

In the interior, populations are closely tied to the surface water available in karstic topography. Dunbar's (1988) review of Paleoindian site location in Florida indicates a strong correlation between site density and surface topography, with 71% of sites occurring in the Tertiary Karst zone (i.e., karstic formations on the surface, predominant in the northern part of the peninsula) but only 12% in the Outlying Region (i.e., karstic formations under at least 35 m of overburden, including all of South Florida) as defined by Bush (1982) for the Florida Aquifer. Dunbar (1988) accounts for this distribution by pointing to the accessibility of water and knappable lithic raw materials. With the lower water tables of the terminal Pleistocene and Early Holocene, human communities would have been closely tied to such water sources as did exist during the Archaic as well as Paleoindian periods in South Florida. The more arid environments of these periods imply a distribution of human activity even more strongly correlated with coastal and near-coastal zones than that documented by Griffin for later prehistoric times.

Widmer (1988) further models paleoecosystems for successive periods of earlier prehistory. He suggests that the modern distribution of ecosystems was in place by about 2700 BP, and that this distribution began to form around 5500 BP, when rates of transgression slowed sharply and alluvial sedimentation from the changing interior effectively began. Widmer argues that prior to 5500 BP, marine transgression was too rapid to permit any significant establishment of mature mangroves, stands of which in any case would be far less productive than modern forests because of the greatly reduced availability of terrigenous nutrients introduced by runoff from the interior. For Widmer, then, human occupation prior to about 5500 BP was strongly oriented to zones just inland of the coast, attracted by the zone of oases in karstic topography and associated mesic floral communities in an otherwise arid landscape. Widmer also distinguishes zones of potential resource availability, according to degree of karstic topography, abundance of water, and development of productive coastal ecosystems. In this aspect of his model, the zone with highest potential for human exploitation lies in the vicinity of Charlotte Harbor, with some fluctuation through time, while the zone with lowest potential contains all of the current study area off the Southwest Florida coast. Widmer's model thus implies a low intensity of prehistoric activity in the regions addressed in this report, with corresponding low density of archeological sites in areas now covered by Gulf waters.

While the general validity of Widmer's model is conceded, its severity is open to challenge on several grounds. Daniel and Wisenbaker (1987) suggest that surface water sources and runoff may have been more abundant than Widmer's model posits, as a result of (1) greater compression of aquifers because of the increased atmosphere pressure of cooler summer temperatures, resulting in increased artesian activity; and (2) reduced evapotranspiration rates and consequent increased runoff rates that result from predominant grassland communities. These factors may have increased somewhat the availability of water in interior zones during periods of lower sea level. For the

coastal zones, Griffin (1988) cites Chappell and Thom's (1977) study in the Pacific to argue that mature mangroves could in fact become established even under the conditions of Widmer's modelling of the transgression process, because Widmer underestimates the tidal range in which mangroves are successful. The slower rates of transgression implicit in the more recent Holocene curve leaves even more opportunity for the formation of mature mangroves.

Further, Widmer suggests that hypersaline lagoons are the only other possible coastal ecosystem of any consequence prior to 5500 BP. This view is again contingent on high, uninterrupted rates of transgression and on low-to-nonexistent flow of surface water. The first of these assumptions runs contrary to the new transgression curve, and the second contradicts evidence from Florida Bay and Biscayne Bay. In the latter regard, the two bays seem to have been freshwater basins prior to their inundation by seawater around 4000 BP (Hoffmeister 1974; Van Arman 1984). Particularly in the Florida Bay setting, surface runoff would provide estuary-like conditions, while tropical meadows would occupy the shallow water just offshore. Thus, while not as productive as, nor distributed in proportions comparable to, the modern ecosystems, human foraging potential in South Florida was not as restricted as Widmer's model predicts. Widmer also assumes a smooth transgressional process, disregarding both episodic still-stands and Holocene sea levels higher than present. Events of the second kind have important implications for human ecology of prehistoric communities on and adjacent to the modern coastline, but these fall outside the concerns of the current study. However, events of the first kind would generate temporary establishment of more maturely developed successions of littoral ecosystems, thus temporarily offering richer foraging opportunities to human populations.

Locational Models and Archeological Potential

These various considerations help establish predictions for the location of human settlement on the continental shelf. In general, these predictions may be quickly stated as follows:

- Occupation at water depths not exceeding 50 m.
- Occupation in vicinity of karstic features.
- Occupation and quarries on drowned stream channels and rock outcrops within these channels.
- Occupation in association with drowned coastal features, and especially in conjunction with coastal peat deposits.
- Activity near outcroppings of lithic raw materials.

Survivability

The survivability of a drowned prehistoric resource is determined by a number of factors. First, sea level rise (transgression) may eliminate, modify, or protect the resource (all of these effects are possible on the South Florida shelf). Second, currents may affect the integrity of the original transgressive sand sheet as water depths increase. Third, storm-generated currents may scour, cover, or otherwise modify the sand sheet. Sediment loading from runoff of surface water from the land may cover resources, although this effect is limited or nonexistent on the South Florida shelf, because the area lacks large rivers. Finally, the modification of the resources' local chemistry through waterborne chemicals, oil spills, or other sources may drastically modify the

preservation characteristics and thus the survivability of materials that would otherwise remain intact.

Because the bathymetric characteristics of the study area are so variable, these general statements need to be assessed for at least two zones: (1) the gently sloping shelf off Southwest Florida; and (2) the ocean side of the Florida Keys, Marquesas Keys, and Dry Tortugas. As corollaries to their divergent topographies, these two zones present different versions of the Holocene transgressive process and of recent sedimentation history, provide disparate paleoecological potential for prehistoric occupation, and engender different processes of site burial and potential forces of site disturbance. A third potential bathymetric unit, Florida Bay, need not be considered here, as it lies inside the Three League Line (see **Figure 10.1**) and so would not be affected by routine oil and gas operations in Federal waters.

Southwest Florida

The nearshore continental margin of South Florida has as foundation a karstic surface probably developed in Miocene strata and overlain by subsequent depositional units. The inner shelf, which extends to about -70 m, is characterized by circular depressions up to 2 km (1 nmi) across, believed to represent a karstic topography; these features are prevalent to a depth of -40 m, and are covered by Recent sediments that thicken as they extend seaward and achieve depths of 10 m in the southern portion of the margin (see **Chapter 2**). This buried karstic topography satisfies two fundamental predictors of prehistoric site location, namely, depths up to -50 m and presence of potential sources of groundwater. The other predictors of site location are less evidently present in the inner margin of the shelf. Drowned drainages have been reported in water of 40 to 60 m north of Sanibel Island (Ballard and Uchupi 1970), outside the study area. Although no definite drainages are reported further south, the existence of such channels as a consequence of runoff from karstic springs seems probable; these channels would be relatively shallow and now masked by subsequent sedimentation. Similarly, drowned coastal features are reported at depths in excess of 50 m, notably near the 80-m, 70-m, and 60-m bathymetric contours, and again less continuously between the 40-m and 18-m bathymetric contours (Coastal Environments, Inc. 1977). In light of the current understanding of Holocene transgression, human occupation is potentially located with respect only to features within the latter set of bathymetric contours. These features, which seem to represent barrier beach and barrier spit complexes, are once again outside the study area, but their presence here suggests a likelihood that similar features exist in the area of concern.

The various topographic elements suggest that the inner margin of the continental shelf provided habitats suitable for human exploitation, though the resulting occupations were less dense than those demonstrated for the more recent periods of South Florida prehistory. In particular, the presence of sinkholes potentially offers the resources of the more mesic habitats attractive to occupation away from terminal Pleistocene and Early Holocene shorelines, which themselves contained modestly rich ecosystems. The gentle slope and relatively low energy of the inner margin of the continental shelf in South Florida also imply relatively rapid burial of sites and anthropogenic deposits, and correspondingly low intensity of post-depositional disturbance or destruction by wave or current action, thus promoting high degrees of site integrity. In sum, then, this zone presents a high probability of encountering prehistoric sites during oil and gas drilling and associated operations. Avoidance of adverse effects upon prehistoric sites can be achieved by locating these activities away from obvious topographic features that predict site location between the Three League Line and the 50-m bathymetric contour.

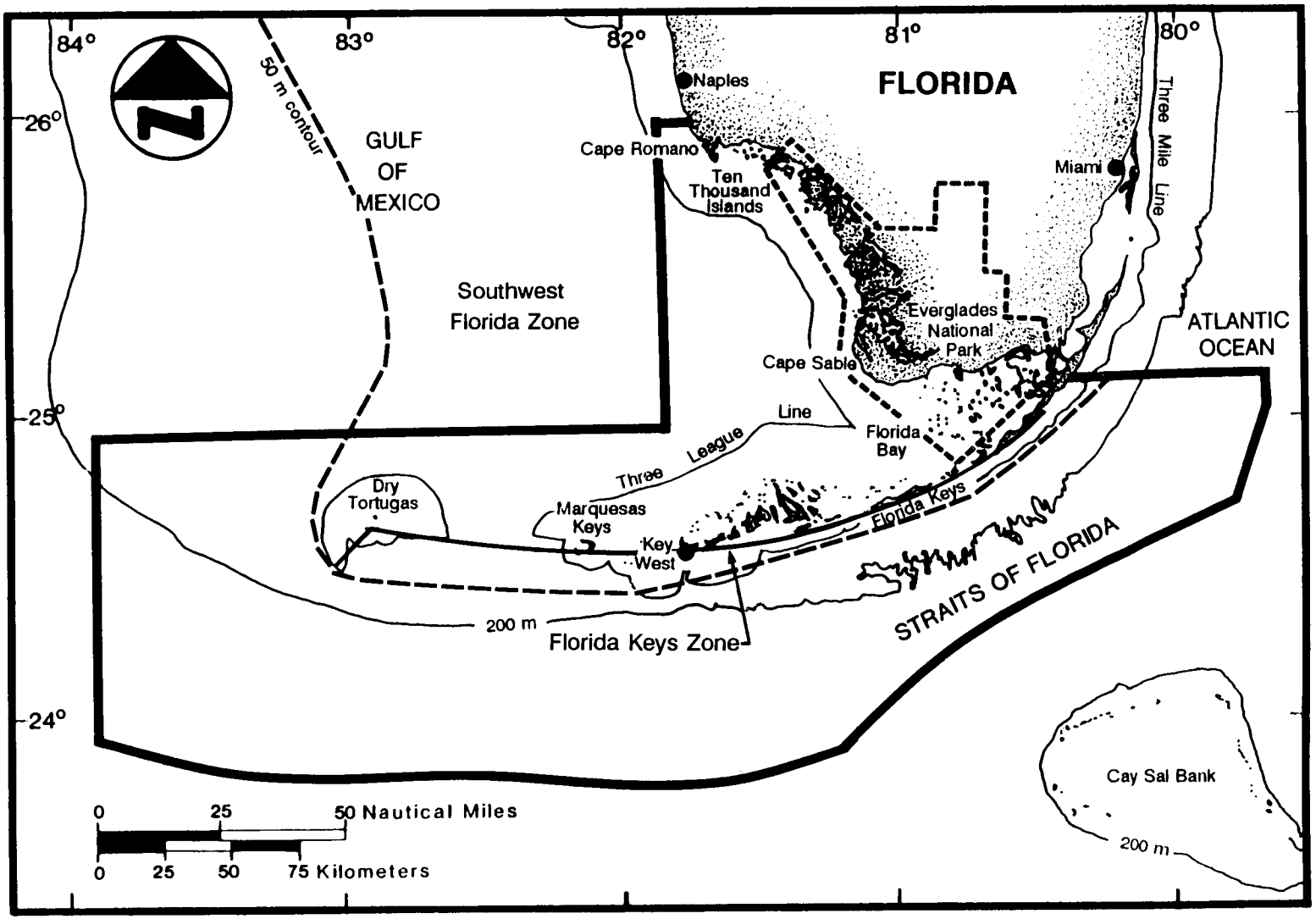

Figure 10.1. Zones of potential prehistoric site locations in and near the study area. Southwest Florida and the Florida Keys are discussed separately in the text. The 50-m depth contour (dashed line) is the presumed outer boundary for prehistoric sites on the continental shelf.

In addition, remote sensing techniques, especially high-resolution seismic reflection profiling, must be applied to oil and gas lease areas in order to locate those shallower topographic predictors now buried by more recent sediments.

The Florida Keys

The surficial geology of the Florida Keys is formed by Pleistocene limestones; the fringes of these islands toward the Straits of Florida (i.e., the Florida Reef Tract) are capped with Holocene sediments, notably coral reefs, coral rubble, carbonate reef sand and mud, unconformably lying on the Pleistocene formations. The Holocene deposits may attain considerable thicknesses, often in excess of 10 m, and sometimes extend over peat deposits at their base. The Marquesas Keys and Dry Tortugas are both formed by Holocene sediments; at the Dry Tortugas, these Holocene reef sediments are 14 m thick and again overlie Pleistocene limestones (Shinn et al. 1989). Holocene formations are not uniformly present through the area, however, as Pleistocene sediments are exposed in pockets that represent 5 to 25% of the bottom surface (see **Chapter 2**). Seaward of this fringe of Holocene deposition, the shelf drops off quickly, over 100 m in 5 km (2.7 nmi).

This general configuration and recent sedimentary history suggest that prehistoric occupation will be difficult to observe in this zone. The steep slope of the seabed off the Florida Keys implies that inundation was not as rapid here as off Southwest Florida, thus permitting establishment of more mature ecosystems that might attract human exploitation, especially of shellfish. But high-energy ecosystems ill-supplied with freshwater runoff are poor relative to others in South Florida, and more recent prehistoric occupation of the Florida Keys seems to have been oriented toward Florida Bay rather than the Straits of Florida (Griffin 1988). Thus the probability of site location in the Florida Keys must be considered low. Furthermore, such sites as did exist will have been heavily affected by post-depositional forces. The steepness of offshore slope entails relatively long-lasting erosional effects of horizontally slow-moving transgression, thus ensuring the natural destruction or disturbance of many sites. Many more sites will have been buried under the extensive Holocene sedimentation, and will thus lack any surface topographic indication of locational potential; in this situation, only application of remote sensing techniques will allow prediction of prehistoric site location.

In general, then, the Florida Keys must be regarded as a zone of relatively low site potential, both because of low original site densities and because of post-depositional disturbance. In any case, the zone of potential effects to prehistoric sites by offshore drilling and associated activities is confined to the narrow strip between the Three League Line and the -50 m contour. Potential effects of routine operations may be entirely avoided if these activities are conducted outside this narrow strip.

Detectability

The predictive models for prehistoric site location presented in this section rely on topographic features such as karstic depressions, stream channels, drowned coastal formations, and "knappable" lithic outcrops in conjunction with depths not greater than 50 m. The model predicts that these features presented to aboriginal communities between 12,000 and 4000 BP the attractions of surface water, relatively rich subsistence opportunities, and knappable raw material, with the consequence that regional prehistoric activity focused around these topographic features. Detection of archeological sites now submerged by transgressive seas is therefore predicated on the distribution of these kinds of features on the inner continental shelf bed.

Aboriginal sites of the Late Archaic and later periods include very large villages as well as smaller habitation and special-activity sites of lower density and duration of occupation. This settlement pattern is the result of long-term population growth and adaptive trends springing from the changing environment of South Florida. The State Plan (Florida Department of State, Division of Historical Resources in prep.) presents a series of site types for successive periods, derived from a fundamentally shore-based data set that represents regional land-use patterns that were essentially truncated by rising sea levels. Therefore, all the possible types of Paleoindian and earlier Archaic occupation of paleoshorelines are not necessarily represented in the State Plan's listing of archeological site types. The kinds of sites expected for the Paleoindian period include (1) relatively large and dense base camps or villages near sources of fresh water and outcrops of lithic raw materials, that contain evidence for multiple functions and so a diversity of tool kits, as well as evidence of stone tool manufacture and maintenance and a relatively wide range of faunal and botanical evidence for subsistence; (2) relatively small, short-term camps and/or kill sites, represented by thinner lithic scatters with evidence for restricted or specialized ranges of function and maintenance of tool kits, and a narrow range of evidence for subsistence; (3) quarry sites at sources of raw material, where blocks of knappable stone are extracted and reduced to varying degrees, but which contain evidence for few additional behavioral patterns; and (4) isolated points. The Archaic periods add to this range of site types a fifth category, namely (5) cemeteries, which are usually associated with freshwater basins but also sometimes with shell middens and solution depressions.

This range of site types holds important potential implication for site detection on the inner continental shelf: because the short-term sites and isolated points are less closely tied to the topographic predictors of site location presented in this study, and because their ephemeral nature is not conducive to thick anthropogenic sedimentation, most of these sites are less likely to be detected with the methods recommended here. Judging by Griffin's (1988) review of more recent prehistoric settlement patterns in the Everglades, these less visible sites may represent as much as 50% of all submerged prehistoric sites, thus leaving underrepresented important aspects of the prehistoric adaptation to the regional landscape prior to the emergence of modern conditions. By the same token, these smaller sites are more subject to post-depositional disturbance or destruction by the transgressive process and by later current scouring, storm erosion, and other high-energy forces, introducing a further bias into the offshore archeological record. Excepting only glades-like environments where sites are predictably located on small tree islands (by analogy with the later prehistoric record; Griffin 1988), small ephemeral sites are not readily detectable with current models and technology. This inability represents a serious gap in current method and information.

Detection of the predictors of prehistoric site location depends on the degree of sedimentation subsequent to inundation. In zones with little or no sedimentation, the predictors are open to surface inspection, either by direct visual identification (e.g., by divers or cameras) or by side-scan sonar. The direct visual approach to detection has already reaped results at Ray Hole Spring, where the solution depression was found by sport divers and then subsequently probed by test excavations that located possible indications of prehistoric activity around the margins of the depression. Side-scan sonar is usually applied to shipwrecks (see below, this chapter). The same technique is also useful in locating potential lithic outcrops, barrier beaches, and other predictors of site location, and may also locate drowned shell middens.

Detection of locational predictors that are buried under recent sediments is best achieved with a combination of high-resolution seismic profiling and vibracoring. The first technique reveals buried surfaces that contain locational predictors, and is used successfully in both geological and archeological remote sensing. The archeological

work on the Sabine River off the Texas and Louisiana coast used seismic techniques to identify locational predictors in the nearshore zone of this portion of the Gulf of Mexico (Coastal Environments, Inc. 1986). Areas of high archeological potential were then tested with the extraction of vibracores, which were then analyzed by grain-size, point-count, and geochemical models of archeological site characterization (Coastal Environments, Inc. 1982). This analysis revealed two possible archeological sites buried under 4 to 7 m of sediment (Coastal Environments, Inc. 1986). It is also possible that the so-called "gassy sediments" detected in shallow hazard surveys are indicators of drowned floral material and are predictors of site location.

Recoverability

The techniques of site detection normally isolate the topographic predictors of site location and/or high probability of the presence of an archeological site. Confirmation, exploration, and evaluation of sites, on the other hand, require more extensive and direct methods. Such methods normally include some combination of coring and broader surface exposures by excavation. The recent work at Ray Hole Spring explored the karstic feature with a combination of diving reconnaissance, coring, and excavation by couple jet; this work was most successful around the margins of the feature, where both environmental information and possible cultural materials were recovered from a large crevice.

Special care must be taken in dealing with submerged archeological sites, because they fall within the broader category of wet sites and therefore potentially contain a range of materials not normally found in dry sites (see Doran 1988). In particular, the proper conditions of site environment may preserve artifacts of wood, leather, fiber, and other organic materials, and better preserve the range of evidence for subsistence than would ordinarily be seen in dry sites. While remarkable preservation is found in some onshore wet sites such as Windover, Little Salt Spring, and Warm Mineral Springs, most of these contexts pertain to the Middle Archaic and later. Discovery and recovery of earlier-period sites with comparable preservation would signally add to the knowledge of the prehistory of Florida and North America.

LOST VESSELS

Humans have used the sea as a source of food and raw materials and as a transportation route for thousands of years. This use nourished the development of a wide range of vessels from prehistoric to modern times. As we can expect from modern examples, many of these vessels were lost to storms, navigational hazards, or other situations and sank or drifted to their final resting places. In South Florida, the Calusa had developed a fully functional maritime tradition by the time of Spanish contact (Florida Department of State, Division of Historical Resources in prep.). We can confidently expect that remains of prehistoric maritime vessels and of wrecked shipping of the historic period exist on the shelf, along its inner margins, and in the intertidal zones. These vessels compose a class of resources little studied until recently, which have nevertheless demonstrated their value in contributing to our understanding of the past, its peoples, and the forces that shaped their lives and still shape ours.

To establish a framework for evaluation of these resources, we rely on the archeological contexts found in *Florida's Comprehensive Historic Preservation Plan* (Florida Department of State, Division of Historical Resources in prep.). This framework will be used in the event submerged cultural resources should be encountered and it becomes necessary to make decisions regarding their significance. For the purposes of this report, we will begin the discussion of these contexts with the

Caloosahatchee Region archeological context and proceed to the context titled World War II and Aftermath.

Included with the contexts are tables identifying a sampling of currently known shipwrecks in the South Florida area. This sample does not in any way represent the full range of known wrecks, let alone the as-yet-unknown wrecks in the study area. It is presented to give the reader a sense of the range of locations, wreck causes, types of vessels, and national origins of shipwrecks in the South Florida region during specific time periods. A major influence on the nature of shipping in the study area during the historic period was the existence of the Florida Keys, as both a destination and a source of navigational hazards. Therefore, our discussion of historic period archeological contexts focuses principally on the history of the Keys.

In addition to the archeological contexts used to delineate the historical development of the study area, a discussion of the growth of commerce and industry and other factors governing shipwreck occurrence helps to refine our ability to predict lost-vessel location. An evaluation of previous research and the development of predictive models completes our discussion of the distribution and density of lost-vessel remains. For our purposes, this discussion is equivalent to the discussion of habitability for drowned prehistoric resources, because it helps to explain the origin, distribution, and probable condition of lost vessels.

Archeological Contexts

The Caloosahatchee Region (4000 BP to Contact)

In late prehistory, the Caloosahatchee region provided the focus of the Calusa, whose complex sociopolitical organization was founded on foraging for maritime resources. The aquatic environments of the region provided not just the subsistence basis for this hunting/gathering society, but also an important means of communication and transportation. In the latter regard, Calusan canoes used interior freshwater zones, nearshore environments, and deeper offshore waters in their subsistence efforts, for transportation of tribute to chiefly centers, and in the passing of information between regions. The greater part of these movements occurred in nearshore and freshwater zones, where artificial canals facilitated passage around political centers. While these sorts of aboriginal shipping will not appear on the inner continental shelf, other, more truly maritime activities may have left their traces. These potentially include offshore line fishing and trading into the Antilles.

Widmer (1986) considers the archeological evidence for offshore line fishing and the sociopolitical implications of this practice for Southwest Florida. While this aboriginal technology was certainly present in the Caloosahatchee region, its contribution to the total subsistence regime seems to have been secondary to nearshore and onshore resources. Even so, the aboriginal canoes used in this effort are doubtless represented among the submerged cultural resources present on the inner continental shelf. The other aboriginal offshore activity was trade and travel between Southwest Florida and the Antilles, especially Cuba. Such communication is well attested in the ethnohistoric record as existing at the time of Spanish contact and intensifying through the 17th and 18th centuries. The vessels used in this trade included canoes and double canoes with attached platforms (see Griffin 1988). Although not definitively documented in pre-Columbian contexts, such trade surely existed, though less intensely, during those earlier periods as well. Thus, seagoing canoes of both pre-and post-Columbian date are also likely to be found among the cultural properties on the continental shelf along the Straits of Florida.

South and Southeast Florida (2500 BP [500 BC] to Contact)

Calusa dominion extended through most of South Florida; therefore, the comments made for the Caloosahatchee region also apply to South and Southeast Florida, with several modifications pertaining to offshore activities. The offshore line fishing that is apparent in the Caloosahatchee region is not yet documented further south, where the technology itself seems absent and the corresponding species of fish are not included in faunal assemblages (Griffin 1988). Although this negative evidence may be overturned by future research, offshore fishing seems not to have been part of the South Florida aboriginal subsistence strategy, and these waters will probably not contain sunken fishing canoes of local origin. As in the Caloosahatchee region, long-distance maritime trade also connected South Florida with islands to the south; these movements are attested in the ethnohistorical record, and are suggested by some stylistic parallels between Antilles pottery and that known as Glades IIIa (i.e., around AD 1200) (Griffin 1988). Contact with the Bahamas is also likely, being documented in the 18th century but not firmly identified in pre-Columbian contexts. A third aspect of maritime travel in South Florida is the seasonal movements, known for the contact period and possible also in the pre-Columbian setting, that integrated Biscayne Bay, the Florida Keys, and Cape Sable in an annual round focused on Florida Bay (Griffin 1988). Most of this seasonal movement occurred landward of the Florida Keys; even so, some of the movement may have followed the seaward line of the Florida Keys and may be represented by sunken canoes in the Reef Tract or in the Straits of Florida.

First Spanish Period (1513 to 1763)

The history of the Florida Keys from the time of European discovery until well after what is now Florida passed into British control in the 1760s strongly reflects the apprehension these low, desolate, and, until this century, isolated rocky islands engendered in virtually all who encountered them. The Spanish name for the Keys, *Los Martires*, was bestowed by the explorer Juan Ponce de Leon, who sighted the islands while rounding the southern end of the peninsula on his way into the eastern Gulf of Mexico during his 1513 voyage of discovery. He noted that, "...the high rocks at a distance look like men that are suffering" (quoted in Morrison 1974). On his return south in June of that year, Ponce de Leon actually stopped within the study area at the Dry Tortugas, which he named for the plentiful turtles found on the several keys in that group of islands. Upon returning to Spain, Ponce de Leon received a royal grant to colonize the newly discovered lands.

Four years later, the Cordoba expedition also made landfall in Florida, where the pilot, Anton de Alaminos, a veteran of Christopher Columbus' second voyage and Ponce de Leon's expedition of 1513, was wounded in a struggle with the natives. They sailed to the Florida Keys before returning to Havana. Alaminos returned to the northern Gulf Coast of "La Florida" in 1518, as pilot for a small fleet under Alonso Alvarez de Pineda, in search of a strait to India. Landing in Southwest Florida, they again encountered hostile natives. Later, this expedition went on to discover the mouth of the Mississippi River.

The fact that the Spanish paid little serious attention to this area until the late 17th century was not the result of indifference or complacency, as some have speculated, but came about as a result of a redirection of Spanish priorities brought on by the disastrous performance of the de Narvaez, de Soto, and de Luna expeditions to La Florida in the mid 16th century. The loss of life was almost 99% in the first and nearly 50% in the second; the third, a colonization effort, had to be ordered home by the Viceroy of Nueva Espana to prevent a repeat of the fate of the first two expeditions.

As a consequence of these reversals and a resulting royal edict, Spanish interest in the Florida Keys became for a time navigational rather than colonial. There was little detectable concern during this period about competition from other European countries. Spain evidently was content to look upon La Florida, including the peninsula and the Florida Keys, as an almost uninhabitable possession occupied by extremely hostile natives who would probably hold their own against colonists of any nationality. The peninsula in effect became a land mass around which Spanish ships from New Spain were forced to sail in returning to Europe. In retrospect, the failure of Spanish efforts to establish a permanent colony in the Santa Elena area on the Atlantic Coast in the mid 1650s can be seen as a turning point in Spain's fortunes in the New World.

The Spanish had originally looked upon La Florida as a potential base from which to protect shipping "shooting north through the Strait of Florida" by the power of the Gulf Stream (Morrison 1974). Early Spanish settlements concentrated primarily in the Caribbean, where the ports of Havana, Puerto Plata, and San Juan serviced vessels returning to Spain via the "Old Bahama Channel." By this route, vessels departing Havana for Spain followed a southeasterly course down the northern Cuban coast until they reached the southern Bahamas, whereupon they turned northeast to meet the prevailing westerly winds across the Atlantic. These early sailors faced danger from the reefs and shoals along the Cuban and Bahamian coasts, and endured slow progress through the unfavorable "Horse Latitudes." As a result, many vessels were lost on this route.

With the discovery and charting of the Straits of Florida, Spanish ships increasingly followed the Straits, known to them as the "New Bahama Channel." Though used intermittently during the late 1540s, the New Bahama Channel became more popular after the 1550s. Following this route, vessels out of Havana sailed eastward to Puerto Puercos or Bahia Honda, crossed to the Florida Keys or eastern Bahamas and then sailed northward through the Straits of Florida and up the coast of North America to meet the prevailing westerlies around Cape Hatteras. From there they followed the Gulf Stream home to Spain.

Though comparatively safer than the old route, sailing by way of the New Bahama Channel presented certain hazards to Spanish shipping, particularly in the area of the Florida Keys. To minimize the danger, departures from Havana were timed so that vessels would arrive off Key West or at the southwestern end of Cay Sal Bank during the day. From Cay Sal Bank, a slow overnight cruise under reduced sail could bring the Florida Keys or the Bahama Bank safely in sight by midmorning. When a daylight arrival could not be arranged, Spanish vessels were often ordered to double the watch, reduce sail, and take frequent soundings when near land or in low visibility. Thereafter, vessels proceeded by running long tacks toward the opposite shore in a generally northward direction so as to clear the mouth of the channel north of the Bahama Bank. In bad weather, vessels often clung closer to the Florida coast, running shorter tacks along the Bahama Banks if conditions were favorable.

Navigational control was maintained by pinpointing a trail of identifiable landmarks along the shore. The hazards presented along the voyage required the master to establish the vessel's position regularly. Often ships would steer directly for dangerous coastal reefs in an effort to determine their position (Marx 1975; Coastal Environments, Inc. 1977; Oceanprobe, Inc. 1988; Garrison et al. 1989).

The Spanish decision to divert attention away from La Florida played into French plans to increase their influence in the area. In 1521, French corsairs intercepted one of Cortez' vessels en route to Spain with a cargo of Aztec art and other New World products. French pirates were soon active in the Caribbean, raiding Spanish ports and attacking Spanish vessels throughout the mid 16th century.

Representative vessels lost during the First Spanish Period are listed in **Table 10.1.**

Table 10.1. Representative vessels lost during the First Spanish Period (1513 to 1763).

Name	Date	Location	Circumstance	Country of Origin/ Type of Vessel
Unknown	1525	Cape St. Helens	Lost	Spanish/Caravel
Unknown	1549	Florida Keys	–	–
Unknown	1577	Florida Keys	–	–
Unknown	1578	Florida Keys	–	–
Unknown	1578	Puerto Escondido	Foundered	Spanish/Nao
Unknown	1590	Florida Keys	–	–
Unknown	1595	Alligator Reef	–	–
Unknown	1618	La Boca	Wrecked	Spanish/Patache
Unknown	1619	Florida Keys	–	–
Unknown	1619	Florida Keys	Sank	Spanish
Unknown	1621	Dry Tortugas	Capsized	Spanish/Patache
Unknown	1622	Matecumbe Key	Hurricane	Spanish/Patache
Nuestra Senora del Rosario	1622	Matecumbe Key	Hurricane	Spanish/Galleon
La Margarita	1622	Matecumbe Key	Hurricane	Spanish/Galleon
*8MO141	1622	Matecumbe Key	Hurricane	Spanish/Galleon
Jesus Senora del Rosario	1622	Florida Keys	Hurricane	Spanish/Nao
Capitana	1623	Florida Keys	Wrecked	Spanish/Galleon
Unknown	1630	Florida Keys	Wrecked	Spanish/Galleon
Unknown	1641	Silver Shoals	Hurricane	Spanish/Nao
Unknown	1677	Key West	–	–
Unknown	1677	Key West	Wrecked	Dutch
Unknown	1685	St. Bernards Bay	Wrecked	French
Unknown	1688	Florida Keys	–	/Nao
Unknown	1688	Florida Keys	Lost	Spanish/Nao
Nuestra Senora de Concepcion y San Josephe	1689	Key Largo	Lost	Spanish/Frigate
Unknown	1698	New Providence	Pirates	–
*8MO130 Henrietta Marie	1698	New Ground	–	–
*8MO167	1700	Dry Tortugas	–	–
Unknown	1700	American Shoals	–	English
*8Mo143	1700	Vacas Key	–	–
*8MO90 "Herrera Wreck"	1715	Matecumbe Key	Hurricane	Spanish
*8MO178, Gallo Indiana (Poss.)	1722	Long Key	Hurricane	Spanish
*8MO103 El Aviso Cosulada	1733	Pacific Reef	Hurricane	Spanish
Nuestra Senora de Belem y San Antonio de Padua	1733	Matecumbe Key	Hurricane	Spanish/Nao
Nuestra Senora de Belem y San Juan Bautista	1733	Matecumbe Key	Hurricane	Spanish/Nao
San Francisco de Asis	1733	Long Key	Hurricane	Spanish/Nao
*8MO131, San Rafael	1733	Long Key	Hurricane	Spanish
*8MO133 El Leri	1733	Matecumbe Key	Hurricane	Spanish
San Pedro	1733	Matecumbe Key	Hurricane	Spanish/Nao
Unknown	1733	Rio Seco	Lost	Spanish/Nao
Nuestra Senora Carmen, San Antonia de Padua y Las Animas	1733	Matecumbe Grande	Hurricane	Spanish/Nao
*8MO179 El Poper de Dios	1733	Matecumbe Key	Hurricane	Spanish
El Gran Poder de Dios y Santa Ana	1733	Vacas Key	Hurricane	Spanish/Nao
Nuestra Sen. Rosario, San Antonio y San Vincente Ferrer	1733	Cayo de Vivaros	Hurricane	Spanish
Nuestra Sen. de las Angustias y San Rafael	1733	Cayo de Vivaros	Hurricane	Spanish/Nao
Nuestra Senora de Balvaneda	1733	Cayo Tobamos	Hurricane	Spanish/Galleon
Floridana	1733	Cayo de Vivaros	Hurricane	Spanish/Frigate
Nuestra Senora del Rosario, San Antonio	1733	Cayo de Vivaros	Hurricane	Spanish/Nao
El Infante	1733	Key Largo	Hurricane	Spanish
San Ignacio	1733	Cayo de Bocas	Hurricane	Spanish/Nao
Almirata Nuestra Senora de Balvaneda	1733	Cayo de Vivaros	Hurricane	Spanish/Galleon
*8MO101, San Jose de las Animas	1733	Conch Reef	Hurricane	Spanish/Nao
Nuestra Senora del Populo	1733	Cabeza de los Martires	Hurricane	Spanish
Capitana El Ruybi	1733	Key Largo	Hurricane	Spanish/Galleon
Unknown	1734	Rio Seco	Lost	Spanish
Naffaw	1741	Florida Keys	Lost	English
Unknown	1741	Cayo de Lobos	Lost	Spanish/Frigate
Furte	1742	Florida Keys	Lost	Spanish/Galleon
H.M.S. Tyger	1742	Florida Keys	Lost	English
H.M.S. Looe	1744	Looe Key	Wrecked	English/Frigate
Billander Betty	1744	Looe Key	–	–
Betsey	1752	Gulf of Mexico	Lost	–
Rhode Island	1752	Gulf of Florida	Hurricane	American
Statea	1752	Gulf of Florida	Hurricane	American
May	1752	Gulf of Florida	Hurricane	English
Unknown	1752	Gulf of Florida	Hurricane	Spanish/Schooner
Alexander	1752	Gulf of Florida	Hurricane	English
Unknown	1752	Gulf of Florida	Hurricane	Spanish
Lancaster	1752	Gulf of Florida	Hurricane	English
Dolphin	1752	Gulf of Florida	Hurricane	English
Queen Anne	1752	Gulf of Florida	Hurricane	English

*Florida State Site Number.

British Period (1763 to 1783)

Spanish military power continued to wane during the 17th century as the English made inroads into Spanish territory. When the English finally gained possession of Florida in 1763, King George III divided the territory into East and West Florida, governed from St. Augustine and Pensacola, respectively. Colonial activity in Florida during the 18th century was concentrated primarily around these two settlements. Representative vessels lost during this period are listed in **Table 10.2.**

Table 10.2. Representative vessels lost during the British Period (1763 to 1783).

Name	Date	Location	Circumstance	Country of Origin/ Type of Vessel
Greenville Packet	1765	Dry Tortugas	Stranded	English
General Conway	1766	Florida Keys	Lost	English
Unknown	1768	Straits of Florida	–	–
Jazo E Santa Anna	1768	Straits of Florida	–	Spanish
Anna Theresa	1768	Florida Keys	–	English/Packet Boat
Unknown	1768	Straits of Florida	–	–
San Antonio	1768	Key West	–	Spanish
Unknown	1770	Florida Keys	Storm	Spanish
Unknown	1770	Florida Keys	–	–
Unknown	1771	Straits of Florida	–	–
El Nauva Victoriosa	1771	Key Largo	Sank	Spanish
Unknown	1771	Florida Keys	–	–
Ann & Elizabeth	1774	Florida Keys	Lost	English
Rhee Galley	1774	Florida Keys	Lost	English
Unknown	1775	Matecumbe Key	–	–
Hamilton	1780	Ajax Reef	–	–
Unknown	1782	Florida Keys	Sank	English
Unknown	1782	Florida Keys	–	English

Second Spanish Period (1784 to 1821)

The coastal islands of the Florida Keys were generally ignored until the U.S. asserted territoriality in the area in 1819 (Priestly 1928; Worcester and Schaeffer 1956; Weddle 1985). Following the War of 1812, settlement in the area of what would become the Gulf Coast of the U.S. expanded rapidly. As a result of this growth, commerce and maritime traffic through Gulf and West Indian waters also increased. Representative vessel losses are listed in **Table 10.3.**

Table 10.3. Representative vessels lost during the Second Spanish Period (1784 to 1821).

Name	Date	Location	Circumstance	Country of Origin/ Type of Vessel
Evenly	1788	Florida Keys	Wrecked	English
Fly	1789	Florida Keys	Lost	English
Unknown	1790	Florida Reef	–	–
Lively	1791	Florida Keys	Lost	English/Brig
Unknown	1792	Florida Keys	–	–
Unknown	1792	Carysfort Reef	–	–
Lovely Ann	1792	Florida Keys	Lost	American
HMS Caryford	1793	Carysfort Reef	Lost	English/Frigate
General Clark	1793	Florida Keys	Lost	English
Catherine Green	1794	Florida Keys	Wrecked	English
Noah's Ark	1795	Florida Keys	Lost	American
Speedwell	1796	Carysfort Reef	Lost	English
Maria	1796	Ludberry Reef	Lost	English
Flora	1798	Florida Keys	Lost	English
*8MO138	1800	Delta Shoals	–	–
Hector	1800	Florida Keys	Lost	–
Eagle	1801	Maranzie Reef	Wrecked	American
Britannia	1803	Florida Keys	Lost	English
Unknown	1803	Mocus Reef	Lost	Spanish/Snow
Calliope	1804	Florida Keys	Lost	American
Andromache	1805	Florida Keys	Wrecked	–
Providence	1805	Florida Keys	Wrecked	–
Rattler	1805	Carysfort Reef	Lost	English
HMS Fly	1805	Carysfort Reef	Wrecked	English
Maria	1806	Dry Tortugas	Wrecked	–
Cabinet	1811	Florida Keys	Lost	English
Highlander	1812	Carysfort Reef	Lost	English
Juno	1812	Carysfort Reef	Lost	American
Orion	1812	Florida Keys	Lost	American
Americano	1814	Florida Keys	Stranded	Spanish
Jerusalem	1815	Florida Keys	Lost	–
Watt	1815	Florida Keys	–	–
Unknown	1815	Carysfort Reef	–	–
Unknown	1815	Carysfort Reef	Wrecked	–
Sir John Sherbroke	1816	Dry Tortugas	Wrecked	–
Zanga	1816	Sound Point	Wrecked	–
General Pike	1816	Sound Point	Wrecked	–
Atlas	1816	Gulf of Florida	Wrecked	English
Magdalen	1816	Florida Keys	Wrecked	English
Three Sisters	1816	Carysfort Reef	Lost	English
Cassack	1816	Florida Keys	Wrecked	–
Unknown	1817	Carysfort Reef	–	–
Marquis de Pombal	1817	Florida Keys	Wrecked	Portuguese
Brandt	1817	Carysfort Reef	–	–
Merrimack	1817	Florida Keys	Wrecked	American/Brig
Despatch	1817	Carysfort Reef	Wrecked	American
Anna Maria	1817	Bason Bank	Wrecked	–
Unity	1817	Carysfort Reef	Lost	–
Europa	1817	Florida Keys	Wrecked	–
Betsey	1818	Florida Keys	Lost	American
Unknown	1818	Carysfort Reef	–	–
Solway	1818	Florida Keys	Wrecked	English
Quebec	1818	Florida Keys	Lost	English
Eliza	1818	Carysfort Reef	Lost	–
Acasta	1818	Dry Tortugas	Lost	English
Modeste	1819	Key Largo	Wrecked	French
Annie of Scarborough	1819	Florida Keys	Lost	–
Barilla	1819	Florida Keys	Stranded	American/Brig
Unknown	1819	Florida Keys	–	/Brig
Unknown	1819	Carysfort Reef	–	–
Sandwich	1819	Florida Keys	Wrecked	English
Lively	1819	Florida Keys	Stranded	/Schooner
Hope for Peace	1821	Carysfort Reef	Dismasted	American
Cosmopolite	1821	Florida Keys	Wrecked	–
Unknown	1821	Carysfort Reef	–	/Brig

*Florida State Site Number.

Territorial Period (1821 to 1844)

After Florida became a U.S. territory, American settlers began to occupy locations in the Florida Keys. Remote from the growing troubles with the Seminole in north central and central Florida, which by 1836 were destined to erupt into the Second Seminole War (1835 to 1842), the Keys were considered to be relatively safe and settlement there preceded that in the major part of the peninsula. Representative vessel losses during this period are listed in **Table 10.4.**

The concomitant increase in American shipping, as well as in that attributable to the Caribbean Basin ports, presented an ideal target for pirates operating out of the secluded bays and inlets of West Indian islands and even remote areas of the Gulf of Mexico. Between 1815 and 1823, nearly 3,000 pirate attacks were reported.

To combat this problem, a small squadron under the command of Commodore Daniel Patterson was given the task of patrolling the Gulf. This force had little success in suppressing aggression, however, and its activities were suspended in 1819. American commercial interests then notified Congress that a more effective naval presence was necessary to subdue the pirates. After surveying the harbor of Key West in February and March of 1822, Matthew C. Perry reported:

> "Heretofore the Florida Keys have been the resort of smugglers, New Providence wreckers, and, in fact, of a set of desperadoes who have paid but little regard to either law or honesty. The present establishment, though on a small scale, will I conjecture, ...be enabled to keep these lawless people from this island; but I would suggest the necessity of an early augmentation of force, if it be only for the purpose of enforcing the revenue laws" (U.S. Congress, House 1836).

A new squadron was sent and suffered great losses from a yellow fever epidemic; furthermore, the schooners *Ferret* and *Wild Cat* were lost at sea, while the larger *Alligator* struck a reef east of Key Largo. Nevertheless, the "Mosquito Fleet," as the squadron was called, accomplished its task. By 1830, piracy had been effectively eliminated in West Indian waters. Although the Navy abandoned Thompson's Island in 1826, because of the yellow fever epidemic, the military maintained a presence on the island through most of the 19th century.

Following the Navy's abandonment of Key West, a survey of the Dry Tortugas was conducted in the fall of 1829 to assess the islands' potential as a naval station. Lieutenant Josiah Tattnall reported favorably on the harbor's suitability as a refuge, central location, and strong defensive position in the event of enemy blockade. During the three months that Tattnall was stationed in the Tortugas, he counted 131 vessels, primarily square-rigged and exclusive of fishing smacks or local craft, sailing within sight of the islands during daylight hours. He estimated an equal number passing at night. In March 1830, Secretary of the Navy John Branch advised President Andrew Jackson that the Tortugas had long-term strategic value as a potential naval station. Commodore Perry, however, continued to favor the harbor at Key West, stating that the "advantages of its location, as a military and naval station, have no equal except Gibraltar..." (U.S. Congress, Senate 1836).

Six years later, the Government was still debating the relative merits of Key West and the Dry Tortugas for a naval depot. By this time, however, the Navy Department's position had shifted in favor of Key West. By the latter part of this period, cotton produced in the Florida panhandle and cattle from the Tampa area were among the major commodities shipped through the study area.

Table 10.4. Representative vessels lost during the Territorial Period (1821 to 1844).

Name	Date	Location	Circumstance	Country of Origin/ Type of Vessel
Francis & Lucy	1822	Florida Keys	–	–
Ann of London	1822	Florida Keys	Lost	English
Unknown	1822	Ledbury Reef	–	–
Lady Washington	1822	Ship Island	Hurricane	/Sloop
Unknown	1822	Florida Keys	–	French/Brig
Alligator	1822	Alligator Reef	–	American
Unknown	1822	Carysfort Reef	–	/Brig
Franklin	1823	Florida Keys	Wrecked	American
Leopard	1823	Florida Keys	Lost	American/Sloop
George III	1824	Carysfort Reef	Lost	English
Swift	1824	Long Island	Wrecked	–
Theodore	1824	Florida Keys	–	–
Unknown	1824	Florida Keys	–	/Brig
Sarah	1824	St. Johnsons Bar	Wrecked	English/Brig
Unknown	1824	Carysfort Reef	–	/Brig
Pointe-A-Petre	1824	Florida Keys	Lost	French
Revenge	1825	Key West	–	–
Johan Carl	1825	Florida Keys	Lost	–
Vigilant	1828	Key West	–	–
Nannu	1828	Key West	–	–
Curreo	1829	Carysfort Reef	–	–
Unknown	1829	Ceaser Creek	–	–
Mississippi	1829	Looe Key	–	–
Vineyard	1830	Long Key	Unknown	/Brig
Unknown	1830	Looe Key	–	–
Toison	1831	Key West	–	–
Mt. Hope	1831	Key West	–	–
Henry	1831	Key West	–	–
Florida	1831	Florida Reef	–	–
Splendid	1831	Florida Reef	–	–
Exerton	1831	Dry Tortugas	Wrecked	/Brig
Dumfries	1831	Dry Tortugas	Stranded	American/Sailing ship
Galaxy	1831	Dry Tortugas	Wrecked	/Schooner
Amulet	1831	Florida Keys	–	–
Flora	1836	Dry Tortugas	Wrecked	/Bark
Ohioan	1836	Ocheesee	Burned	American/Steam sidewheel
America	1836	Dry Tortugas	Wrecked	/Sailing ship
Tallahassee	1836	Dry Tortugas	Wrecked	/Sailing ship
Billow	1837	Dry Tortugas	Wrecked	/Brig
Tempest	1838	Ocheesee	Snagged	American/Steam sidewheel
Poacher	1840	Dry Tortugas	Foundered	American/Bark
"Unidentified"	1840	Dry Tortugas	Wrecked	American/Bark
Unknown	1841	Key West	Hurricane	–
Unknown	1841	Sand Key	–	/Packet Boat
Peguot	1842	Key Vacas	–	–
Unknown	1842	Key West	–	/Packet Boat
Alasco	1842	Conch Reef	–	–
Chamois	1842	River Junction	Exploded	American/Steam sidewheel
Axis	1842	Florida Reef	–	–
Cuba	1842	Florida Reef	–	–
Caroline	1842	Key West	–	–
Colonel T. Sheppard	1842	Key West	–	–
Rudolph Groning	1842	Dry Tortugas	Abandoned	American/Brig
Pilgrim	1843	Dry Tortugas	Abandoned	/Brig
Robert Rulton	1843	Iola	Snagged	American/Steam sidewheel
Anson	1843	Key Vacas	–	–
Rebecca	1843	Dry Tortugas	Wrecked	English/Schooner
Zotoff	1844	Dry Tortugas	Wrecked	/Sailing ship
Wellington	1844	Dry Tortugas	Abandoned	English/Sailing ship
Mount Vernon	1844	Carysfort Reef	–	–
California	1844	Crooked River	Capsized	American/Schooner
Unknown	1844	Key West	–	–
Select	1844	Dry Tortugas	Stranded	American/Schooner
Althalia	1844	Key West	–	–

Statehood (1845 to 1860)

During this period, the island of Key West became an important regional harbor for Southwest Florida. In 1845, as part of a Federal coastal fortification program, construction began on Fort Taylor at Key West. The Fort was intended as an outpost to guard against enemy intrusion into the Gulf of Mexico by way of the Straits of Florida. In 1846, however, a hurricane demolished most of the previous year's work. When the Civil War broke out 15 years later, Fort Taylor was still incomplete, as was Fort Jefferson in the Dry Tortugas.

Also during this period, an increasing number of railroad lines began linking interior lands with the Gulf Coast, where timber and agricultural products could be loaded onto ships. Tampa, by this time, was shipping nearly 15,000 head of cattle annually. With an increasing number of steamboats and other shipping, and an antiquated, poorly maintained road system, water began to dominate the land as a transportation medium in many other parts of Florida in addition to the Florida Keys. Representative vessel losses during this period are listed in **Table 10.5.**

Table 10.5. Representative vessels lost during the Statehood period (1845 to 1860).

Name	Date	Location	Circumstance	Country of Origin/ Type of Vessel
Newark	1845	Carysfort Reef	–	–
Tellumah	1845	Ceaser Creek	–	–
Rienzi	1845	Florida Reef	–	–
Mandarin	1846	Key West	Lost	–
H. W. Stafford	1846	Key West	–	–
Lafayette	1846	Key West	–	–
General Wilson	1846	Key West	–	–
Commissary	1846	Key West	–	–
Exchange	1846	Key West	–	–
Melemora	1846	Key West	–	–
Unknown	1846	Key West	Hurricane	–
Warrior	1846	Key West	Sank	–
Water Lily	1846	Key West	Sank	–
Villanueva	1846	Key West	Ashore	–
U. S. Perry	1846	Key West	Lost	–
Saranoh	1846	Key West	Sank	–
Napoleon	1846	Key West	–	–
Olive & Eliza	1846	Key West	–	–
Morris	1846	Key West	–	–
Navigator	1846	Key West	–	–
Warsaw	1846	Key Vacas	–	–
St. Mark	1846	Carysfort Reef	–	–
Platina	1846	Carysfort Reef	–	–
Perry	1846	Florida Reef	–	–
Iris	1846	Florida Reef	–	–
Salon	1847	Key West	Wrecked	/Schooner
St. Mary's	1847	Key West	Wrecked	/Schooner
Persia	1847	Key West	Wrecked	/Brig
Samuel Roberts	1847	Key West	Wrecked	/Schooner
Gilbert Hatfield	1847	Key West	Wrecked	/Brig
Rudolph Groning	1847	Key West	Wrecked	/Brig
Milliaoclat	1847	Key West	Wrecked	/Brig
Samuel Roberts	1847	Key West	Wrecked	/Schooner
John Howell	1847	Dry Tortugas	Burned	/Schooner
Euphrasia	1848	Key West	Wrecked	/Schooner
Hope	1848	Key West	Wrecked	/Schooner
Toure	1848	Key West	Wrecked	/Bark
Elizabeth	1848	Key West	Wrecked	/Brig
Narragansett	1848	Key West	Wrecked	/Steamship
Benjamin Litchfield	1848	Key West	Wrecked	/Brig
Hudson	1848	Key West	Wrecked	/Schooner
Flora	1848	Key West	Wrecked	/Bark
Tagliona	1848	Key West	Wrecked	/Schooner
Arroswick	1848	Key West	Wrecked	/Schooner

Table 10.5. (Continued).

Name	Date	Location	Circumstance	Country of Origin/ Type of Vessel
Brewster	1848	Key West	Wrecked	/Schooner
Canton	1848	Dry Tortugas	Wrecked	/Sailing ship
Madison	1848	Key West	Wrecked	/Brig
Quebec	1848	Key West	Wrecked	/Schooner
Nancy W. Stevens	1849	Dry Tortugas	Wrecked	/Bark
*8MO164	1850	Dry Tortugas	–	–
Sylphide	1850	Dry Tortugas	Wrecked	Swedish/Brig
*8MO170	1850	Dry Tortugas	–	–
*8MO160	1850	Dry Tortugas	–	–
New Orleans	1850	Dry Tortugas	Foundered	/Schooner
New York	1850	Dry Tortugas	Sank	/Schooner
Harriet and Martha	1854	Dry Tortugas	Wrecked	–
Tartar	1855	Dry Tortugas	Wrecked	/Brig
Martha Gilchrist	1858	Dry Tortugas	Wrecked	/Brig
Las Mulas	1860	Man Key	–	–

*Florida State Site Number.

Civil War (1861 to 1865)

Anticipating Florida's secession from the Union, Captain James Milton Brannon, First Artillery, the senior ranking Army officer of Key West, occupied Fort Taylor and placed the island at the disposal of Federal (Union) forces in 1861. Possession of Key West proved to be of immense value to Union strategists:

> "Without secure control of the island, Lincoln's declaration of an effective blockade of the Southern Coast would have been a farce, for the Navy had no other Southern coaling station so necessary for its short cruising range blockading fleets. Early in the War, Southern blockade runners operated quite successfully from Havana and the British controlled Bahamas, however, fast Federal cruisers operating from Key West were to wreak havoc among these vessels during the last three years of the conflict" (Camp 1960).

An average of 32 vessels from the East Gulf Blockading Squadron were based at Key West during the Civil War, while 300 Confederate blockade runners were brought into the port of Key West as prizes after capture (Williams 1954; Schellings 1955; White and Smiley 1959; Griswold 1965; Camp 1960; Florida Department of State, Division of Historical Resources in prep.). Representative vessel losses are listed in **Table 10.6.**

Table 10.6. Representative vessels lost during the Civil War (1861 to 1865).

Name	Date	Location	Circumstance	Country of Origin/ Type of Vessel
Menemom Sanford	1862	Carysfort Reef	Stranded	American/Steam sidewheel
*8MO142	1865	Coffin Patch	–	–
Atlanta	1865	Dry Tortugas	Wrecked	/Brig

*Florida State Site Number.

Reconstruction (1866-1879)

After the war, cattle sales (and thus shipments) resumed. A particularly large customer for cattle was Cuba, thus stimulating production in South Florida. At the same time, Tampa gained in importance as a port city. Representative vessel losses during this period are listed in **Table 10.7.**

The area may have seen some increase in river traffic as a result of burgeoning tourism, but this would have been concentrated in the eastern part of the Florida peninsula area (Florida Department of State, Division of Historical Resources in prep.).

Table 10.7. Representative vessels lost during Reconstruction (1866 to 1879).

Name	Date	Location	Circumstance	Country of Origin/ Type of Vessel
Unknown	1866	Key West	–	–
Tonawanda	1866	Grecian Shoals	Stranded	American/Steam screw
Pampero	1866	Cape Romano	Foundered	American/Steam sidewheel
Unknown	1866	Key West	–	–
Rebecca Barton (21530)	1866	Key West	Foundered	American/Steam screw
Mutter Shultz	1870	American Shoals	–	–
Key West	1870	Key West	–	–
Honduras (10524)	1870	Key West	Stranded	American/Steam sidewheel
Unknown	1870	Key West	–	–
Maria Ferguson	1870	Dry Tortugas	Wrecked	/Brig
Sonora	1872	Dry Tortugas	Wrecked	/Schooner
Unknown	1872	Key West	–	–
Nor'wester	1872	Key West	Burned	/Clipper
William M. Jones	1875	Dry Tortugas	Wrecked	American/Schooner
Jessie	1875	Brazos	–	American/Steam sidewheel
Unknown	1875	Florida Keys	–	–
Henry J. May	1875	Dry Tortugas	Wrecked	/Schooner
Unknown	1875	Key West	–	–
Mezzie	1877	Dry Tortugas	Wrecked	English/Brig

Post-Reconstruction (1880 to 1897)

By 1890, the seven leading industries in the State were lumber, cigar and cigarette production, turpentine, fertilizers, ship- and boat building, and railroad-car and shop construction. Several of these products, including cattle bound for Cuba, were shipped from Gulf ports such as Tampa and Pensacola (Florida Department of State, Division of Historical Resources in prep.). Much of this traffic passed through the study area and contributed, on occasion, to the tally of submerged cultural resources found off the Florida Keys today. Representative vessel losses are listed in **Table 10.8.**

On 2 August 1882, Congress appropriated $25,000 to dredge an experimental 90-m-wide, 5-m-deep channel across the Northwest Channel bar at Key West. The U.S. Army Corps of Engineers completed the work the following year, but by 1884 the channel had refilled. The Corps then abandoned plans to maintain a dredged channel across the bar.

The Rivers and Harbors Act of 1886 authorized a survey of the entrance to Key West Harbor. Captain W. M. Black submitted his report of the survey in June 1887. On the basis of soundings, borings, and systematic observation of tides and currents, Black recommended the construction of a riprap coral jetty 560 m long along the west

Table 10.8. Representative vessels lost during Post-Reconstruction (1880 to 1897).

Name	Date	Location	Circumstance	Country of Origin/ Type of Vessel
Unknown	1881	Key West	–	–
Joseph Baker	1881	Dry Tortugas	Stranded	American/Bark
Tolomeo	1881	Dry Tortugas	Wrecked	Italian/Bark
Lucy M	1881	Key West	Sprung Leak	American/Schooner
Unknown	1882	Florida Keys	Wrecked	French/Brig
R. B. Gove	1882	Dry Tortugas	Wrecked	American/Brig
Gutenberg	1885	Dry Tortugas	Wrecked	German/Bark
Charles R. Campbell	1886	Dry Tortugas	Abandoned	American/Schooner
Arietas	1886	Dry Tortugas	Lost	/Schooner
Outing	1887	Gilbert's Bar	Unknown	/Sloop
Arthur	1887	Dry Tortugas	Abandoned	/Brig
Sebulon	1887	Dry Tortugas	Stranded	Norwegian/Bark
Joshua H. Marvell	1887	Dry Tortugas	Unknown	/Schooner
Freddie L. Porter	1887	Dry Tortugas	Abandoned	/Schooner
Slobodna	1887	Molasses Reef	Unknown	/Steamship
Prince Umberto	1888	Duck Key	Unknown	/Bark
Adelaide Baker	1889	Coffin Patch	–	/Bark
True Briton	1889	Rebecca Shoals	Unknown	/Ship
Erl King	1891	Long Reef	Unknown	/Steam screw
Edda	1891	Straits of Florida	Unknown	/Bark
Shannon	1892	Dry Tortugas	Wrecked	American/Brig
Arcadia	1893	Dry Tortugas	Wrecked	English/Brig
Carmalita Composite	1893	Dry Tortugas	Wrecked	/Bark
Ceres	1894	Dry Tortugas	Wrecked	–
Beatrice	1895	Dry Tortugas	Wrecked	English/Schooner
Shelter Island	1896	Looe Key	–	–
Unknown	1897	Key West	–	–
Clyde (5001)	1897	Key West	Burned	American/Steam screw

*Florida State Site Number.

side of Northwest Channel, "with the view of turning the entire flood currents of the northwest channel across the bar, and the expectation of thus clearing the channel without dredging" (U.S. Congress, Senate 1888). The $600,000 project would create a 5.2-m channel which was expected to result in an "enormous increase" in the 2,500 tons of shipping passing through the channel daily. Shipmasters operating out of Key West supported the plan to deepen the channel:

> "The steamers of this [Plant] line could enter and leave at all times, also the Mallory and Morgan lines steamers that touch at Key West and leave for New Orleans and Galveston could pass out at any stage of tide and make a straight course in comparatively smooth water with no dangers from tides or winds from southwest around by south to northwest; all sailing vessels trading in the lumber and cotton business could pass through for Cedar Keys, Pensacola and New Orleans, and Galveston" (U.S. Congress, House 1889b).

The Board of Engineers concurred with Black's observations, but found the plan "unlike an ordinary harbor improvement in that the bar to be removed is remote from the shore where success must wholly depend upon the proper regulation of conflicting tidal currents, with no assistance from permanent banks upon which to base the needful training wall" (U.S. Congress, House 1889a). Black was ordered to conduct further observations and take borings of the channel bottom down to bedrock.

Black's second survey confirmed that the bar was caused by the confluence of two tidal currents, the first running north and south through the channel, the second following an east/west course along the northern side of the reef. The survey also

discovered that the channel was underlain by rock at a depth of 7.3 m, mean low tide, forming a natural sand-filled ravine 300 m wide. Black modified his proposal to create a channel 7.3 m deep at a projected cost of $1,500,000. The Corps concurred with the modifications, but deemed it unwise to attempt the full 7.3 m depth: "in a work of so novel a character, no prediction can safely be made" (U.S. Congress, House 1889a).

In April of 1896, Captain W. C. Wise of the U.S.S. *Amphitrite* complained of wrecks obstructing navigation in Man of War Harbor at Key West. In June, the Secretary of War authorized $27,000 for the removal of the barks *Marcelo*, *Brandon*, *Anto*, and *Almora*, the schooners *Adelaide Baker* and *Rosalie*, the ship *Marie Frederika*, the steamers *Governor Marvin* and *Cochran*, and the old dry dock. The project was completed in 1898.

Turn of the Century (1898 to 1916)

Key West also played an important role in the Spanish American War. With the outbreak of war, activity in Key West intensified. Situated only 150 km (80 nmi) from Cuba, it became an important supply depot and coaling station for the ships of the Atlantic Squadron. The military and naval establishments on the island were initially overwhelmed by the influx of supplies and ammunition, and especially coal. Private warehouses and docking facilities were leased, while coal was stored on barges anchored in the harbor as a stopgap measure until completion of construction on bunkers designed to hold 15,000 tons. Only after construction had begun did anyone realize that shallow water prevented the naval vessels from approaching within 10 km (5.4 nmi) of the bunkers. As a result, the barges continued to operate as coaling vessels until a channel could be dredged through the harbor to give access to the fleet. Meanwhile, in the Dry Tortugas, old bunkers were refurbished and new ones built for an additional capacity of 20,000 tons.

The Spanish-American War proved once again Key West's importance as a naval base. The difficulty in getting warships into the harbor had created concern, however. Consequently, in 1902, the Navy Department conveyed to the Corps of Engineers the desirability of improving Man of War Harbor to allow access for deep-draft vessels:

> "The needs of the Navy would be attained if Man of War Harbor were dredged between the 18-foot curves to a depth of 30 feet and the approaches cleared for a main ship channel to the depth of 33 feet. These improvements would only give anchorage space for a limited number of large vessels, but by means of suitable dolphins along the sides of Man of War Harbor, placed sufficiently close to permit the proper securing of vessels, a large number would be provided for" (U.S. Congress, House 1904).

The Corps duly surveyed the Harbor and estimated the cost of improving the Channel according to the Navy's requirements at $10,317,000. In 1904, the Board and Chief of Engineers concluded that given the expense, it was inadvisable to undertake any further improvements at Key West beyond the jetty construction in progress (U.S. Congress, House 1904).

In February 1908, H. H. Raymond, Vice-President and General Manager of the Mallory Steamship Company, wrote his senator about uncharted obstructions to navigation in Key West Harbor. The Chief of Engineers reported directly to Senator Taliaferro that the obstructions represented previously unknown coral reefs that did indeed obstruct navigation, but inasmuch as they were located outside the boundaries of currently authorized improvement projects, an act of Congress would be required for their removal. Shortly thereafter, a bill authorizing the diversion of up to $5,000 from

the Key West Harbor improvement project to cover the cost of removing the obstructions was recommended for passage in both houses of Congress (U.S. Congress, House 1908; U.S. Congress, Senate 1908).

Until the early 20th century, all transportation through the Florida Keys, whether of people or of goods, was carried out by boat. In 1861, for example, Captain Brannon (who seized Fort Taylor for the Union forces in 1861) was entirely dependent on the Mordecai and Company steamer *Isabel*, sailing biweekly between Charleston and Key West, or on passing ships out of New Orleans or St. Marks, for the transportation of communiques to and from headquarters in Washington. In 1912, however, Henry M. Flagler completed the multimillion-dollar Florida East Coast Railway to Key West. After relative isolation for almost a century, residents of the Florida Keys now had the opportunity to travel overland to the mainland. Many took the opportunity and moved on.

Representative vessel losses during the Turn of the Century period are listed below in **Table 10.9.**

Table 10.9. Representative vessels lost during the Turn of the Century (1898 to 1916).

Name	Date	Location	Circumstance	Country of Origin/ Type of Vessel
Osmond	1898	Dry Tortugas	Wrecked	Norwegian/Bark
*8SL73	1900	Old Prince Inlet	–	–
Unknown	1900	Delta Shoals	–	–
Nellie M. Slade	1900	Dry Tortugas	Wrecked	/Bark
A. Hayford	1905	Dry Tortugas	Wrecked	/Schooner
Withlacoochee No. 9	1906	Port Inglis	Foundered	Spanish/Nao
S. O. Co. No. 90	1906	Dry Tortugas	Foundered	/Schooner
Mount Pleasant	1906	Plantation Key	Burned	/Gas screw
Flora	1906	Key Largo	Foundered	American/Schooner
Adam W. Spies	1906	Stirrup Key	Stranded	/Schooner
Sidney	1907	Matecumbe Key	Foundered	/Schooner
Long Key	1907	Long Key	Stranded	/Gas screw
Sego	1907	Sanborns Landing	Sank	/Steamship
Thistle	1907	Key Largo	Stranded	/Gas screw
Irene	1907	Dry Tortugas	Wrecked	/Schooner
Manatee	1908	Key West	Burned	American/Schooner
Ethel	1909	Key West	Foundered	/Schooner
Freddie W. Alton	1909	Key West	Collided	/Schooner
Floria	1909	Key West	Stranded	/Gas screw
Elizabeth Ann	1909	Key West	Foundered	/Schooner
Carmen	1909	Key West	Foundered	/Sloop
Rosebud	1909	Key West	Foundered	/Schooner
Gertrude	1909	Key West	Foundered	/Schooner
Empire	1909	Key West	Foundered	/Gas screw
Braganza	1909	Key West	Foundered	/Schooner
Kate Davis	1909	Key West	Foundered	/Schooner
Medford	1909	Key West	Stranded	/Schooner
Nettie J	1909	Key West	Foundered	/Steam screw
Kate	1909	Key West	Foundered	/Schooner
Juniata	1909	Key West	Foundered	/Schooner
Reaper	1909	Key West	Foundered	/Sloop
Impulse	1909	Key West	Foundered	/Schooner
Havana	1909	Key West	Foundered	/Sloop
Ada	1909	Key West	Foundered	/Sloop
Volunteer	1909	Sand Key	Foundered	American/Schooner
Wanderer	1909	Florida Bay	Foundered	/Steam sidewheel
Undine	1909	Key West	Collided	/Gas screw
Peerless	1909	Boot Key	Foundered	/Steam sidewheel
Emma Eliza	1909	Cudjoe Key	Foundered	/Schooner
Managua	1909	Cudjoe Key	Stranded	/Schooner
Nannie C. Bohlin	1909	Dry Tortugas	Stranded	/Schooner
Amy	1909	Key West	Foundered	/Schooner

Table 10.9. (Continued).

Name	Date	Location	Circumstance	Country of Origin/ Type of Vessel
Quinnipiac	1909	Key West/Miami	Foundered	American/Gas screw
Unknown	1909	Key West	–	–
Stillman F. Kelly	1909	Salt Key Bank	Stranded	/Schooner
Addie & Norman	1909	Key West	Foundered	/Sloop
S. H. Woodbury	1909	Key West	Foundered	/Schooner
Unknown	1909	Key West	–	–
Unknown	1909	Key West	–	–
Triton	1909	Key West Harbor	Burned	/Schooner
Noal	1909	Key West	Foundered	/Schooner
Saturn	1910	Marco Bar	Stranded	American/Gas screw
Edward T. Stotesbury	1910	Knights Key	Stranded	/Schooner
Eufalia	1910	Beresford	Burned	/Steam sidewheel
Alexander Jones	1910	Fowey Rock	Stranded	/Steam screw
William W. Converse	1910	Halifax River	Stranded	/Schooner
Florida	1910	Dry Tortugas	Foundered	/Schooner
Virginia	1910	Boca Chica	Foundered	/Steam sidewheel
Unknown	1910	Boca Chica	–	–
Columbia	1911	Milton	Burned	/Steam sidewheel
Mary Eliza	1911	Dry Tortugas	Stranded	/Schooner
Florida	1911	Dry Tortugas	Foundered	American/Schooner
Star of the Sea	1911	Florida Reef	Stranded	American/Schooner
Ruth A	1911	Boca Chica	Burned	American/Gas screw
Heartsease	1911	Key West	Foundered	American/Schooner
Winfield S. Shuster	1911	Isaac Shoal	Stranded	/Schooner
S. R. Mallory	1911	Key West	Foundered	/Steamship
Willie Wallace	1911	Florida Reef	Stranded	American/Schooner
C. A. Pierce	1912	Marco	Stranded	American/Gas screw
William R. Wilson	1912	Pickles Reef	Stranded	American/Schooner
Clifford N. Carver	1913	Tennessee Reef	Stranded	/Schooner
Unknown	1913	Tennessee Reef	–	–
Pendleton Brothers	1913	Dry Tortugas	Stranded	/Schooner
Sam'l T. Beacham	1913	Straits of Florida	Collided	/Schooner
Planter	1914	Ft. Myers	Burned	/Steam screw
Edna Louise	1914	Key West	Burned	/Schooner
Amelia	1914	Key West	Burned	/Schooner
Irene Albury	1914	Long Key	Foundered	/Gas screw
Markab	1914	Pigeon Key	Struck Pier	/Schooner

World War I and Aftermath (1917 to 1920)

The World War I period of Florida's history begins with the U.S. entry into the war in Europe and ends the brief postwar depression that affected both the Nation and the State. The war brought some changes to Florida, particularly in the areas of military support and procurement. Shipbuilding, especially in Tampa and Jacksonville, enjoyed a minor boom and Key West became a submarine base and naval training facility.

Domestic activities such as work on the State highway system brought about a decrease in demand for water transportation. As a result, steamer traffic quickly declined as a vehicle for the tourist trade. To make way for new agricultural and residential development, thousands of acres of land below Florida's coastal ridge were drained. Projects in Polk, Pinellas, Manatee, and Lee Counties promoted development in the southwestern portion of the State. Timber, beef, and other products continued to be shipped from Gulf ports and around the peninsula (Florida Department of State, Division of Historical Resources in prep.). Representative vessel losses are listed in **Table 10.10.**

Table 10.10. Representative vessels lost during World War I and Aftermath (1917 to 1920).

Name	Date	Location	Circumstance	Country of Origin/ Type of Vessel
Brazos	1917	Dry Tortugas	Stranded	/Schooner
Hereward	1917	Stump Pass	Foundered	/Schooner
Diamondfield	1917	Tillman	Foundered	/Schooner
City of Washington	1917	Elbow Reef	Stranded	/Schooner
Lake City	1918	Key West	Collided	/Steam screw, Cargo
Unknown	1918	American Shoals	–	–
Bessie Whiting	1918	Perico Island	Stranded	/Schooner
Robert	1918	Key West	Foundered	/Barge
Unknown	1918	Key West	–	–
Unknown	1918	Boca Chica	–	–
Maria Louisa	1918	Dry Tortugas	Wrecked	Greek/Schooner
F. A. Kilburn	1918	American Shoals	Burned	/Steam screw
Lizzie E. Dennison	1918	Hertzel Shoals	Stranded	/Schooner
City of Philadelphia	1919	Punta Rassa	Burned	/Steam screw
Unknown	1919	Delta Shoals	–	–
Louis H	1919	Sombrero Key	Burned	/Barge
Santa Christina	1919	Key West	Burned	/Gas screw
Unknown	1919	Key West	–	–
J. Frank Seavey	1920	Straits of Florida	Foundered	/Schooner
Priscilla L. Ray	1920	Key West	Stranded	/Steam screw
Mayport	1920	Roncador Reef	Stranded	/Steam screw
Unknown	1920	Key West	–	–

Boom Times (1921 to 1929)

The boom period of Florida's history saw spectacular population growth and urban development. Intense land speculation, attributable largely to increased tourism and the availability of reclaimed swampland, characterized the period and was concentrated in the southern half of the State. Accompanying the land boom was an increase in highway and railroad construction. To take advantage of both tourism and revenues from the transportation of agricultural products, two rail lines were extended as far as Naples in 1927. One of these, the Atlantic Coast Line, reached the Everglades later that year. Lumber, turpentine, fertilizers, and tobacco and citrus products continued to be produced and were increasingly exported by railroad rather than by water (Florida Department of State, Division of Historical Resources in prep.). Representative vessel losses during this period are listed in Table 10.11.

Table 10.11. Representative vessels lost during Boom Times (1921 to 1929).

Name	Date	Location	Circumstance	Country of Origin/ Type of Vessel
C. W. Mills	1921	Dry Tortugas	Burned	/Schooner
C. W. Wells	1921	Dry Tortugas	Burned	/Schooner
Pauline G	1921	Key West	Burned	/Gas screw
Lewis H. Goward	1921	Key West	Burned	/Schooner
Bagdad	1921	Key West	Foundered	/Schooner
Unknown	1921	Key West	–	–
Agnes Bell	1921	Dry Tortugas	Lost	/Schooner
Unknown	1921	Boca Chica	–	–
City of Tampa	1921	Bay Point	Burned	/Steam screw
City of Eufala	1921	Neals Landing	Burned	/Steam sidewheel
Pilot	1921	Sand Key	Burned	/Gas screw
Herbert May	1922	Marquesas Reef	Stranded	/Schooner
Caldwell H. Colt	1922	Dry Tortugas	Stranded	/Schooner
Magnolia	1923	Key West	Foundered	/Schooner
John W. Callahan	1923	White River	Stranded	/Steam sidewheel
Four M's	1924	Sugarloaf Key	Burned	–
Lilla	1924	Key West	Foundered	/Gas screw
Carrie S. Allen	1924	Key West	Burned	/Schooner
Eola	1925	Key West	Stranded	/Gas screw
William Russel	1925	Olympia	Foundered	/Schooner
Fannie and Fay	1925	Dry Tortugas	Foundered	/Schooner
Island Belle	1926	Key West	Stranded	/Steam screw
Liberty	1926	Key West	Stranded	/Gas screw
Thendara	1926	Key West	Foundered	/Steamship
Palatka	1926	Mandarin Point	Foundered	/Steam screw
Nancy Hanks	1926	Florida Reef	Stranded	/Schooner
Unknown	1926	Key West	–	–
Unknown	1926	Key West	–	–
Maurice R. Thurlow	1927	Diamond Shoal	Stranded	/Gas screw
Thomas Clooney	1927	Bay Point	Foundered	/Barge
Rose Murphy	1927	Sand Key Light	Foundered	/Steam screw
Unknown	1927	Sand Key Light	–	–
Eclectic	1927	Boca Grande	Stranded	/Gas screw
Swan	1927	Milton	Burned	/Oil screw
Moore No. 3	1927	Great Isaac Light	Foundered	/Barge
Cleo	1927	Key West	Foundered	/Sloop
Albert Meyer	1927	Florida Keys	Stranded	/Schooner
Wm. G. Vance	1927	Key West	Foundered	/Schooner
Unknown	1927	Florida Keys	–	–
Bear Ridge	1927	Hereford Inlet	Collided	/Schooner, Barge
White Squadron	1927	Key West	Foundered	–
John Henry Sherman	1928	Dry Tortugas	Stranded	/Gas screw
Anthony D. Nicholas	1928	Monte del Canejo Light	Burned	/Schooner
Unknown	1928	Key West	–	–
City of Everglades	1928	Collier City	Burned	/Gas screw
Unknown	1928	Sambo Key	–	–
Arago	1928	Sambo Key	Stranded	/Oil screw
Monroe County	1928	Key West	Burned	/Oil screw

Depression and New Deal (1930 to 1940)

From beginning to end of the decade between 1930 and 1940, virtually every measurable aspect of Florida's economic life remained stagnant. Within that period, however, and contrary to popular belief, the economy actually waxed and waned, rebounding in 1935 to 1936, only to collapse again until public expenditures associated with rearmament gave it new life. Land reclamation projects came to a halt as the housing market dwindled away. In 1935, a severe hurricane struck South Florida, destroying so much of the Florida East Coast Railway's "Overseas Railroad" to Key West that the company decided to sell the remainder to the State. The Works Progress Administration (WPA) constructed a road on the former railroad right-of-way, which reopened as the Overseas Highway in 1938 (Florida Department of State, Division of Historical Resources in prep.). Of those that had stayed in the Florida Keys after the

construction of the railroad, the Depression brought grief and ruin to many. In desperation, the local authorities appealed first to the State, then to the Federal government for aid. As a result, a plan was devised to bring a new industry to the Florida Keys: tourism. Labor was solicited from the local population, and under the auspices of the Works Projects Administration, the Florida Keys began to be transformed into a tourist resort (Florida Department of State, Division of Historical Resources in prep.; Corliss 1953; Saunders 1959; Camp 1960; Long 1968). Representative vessel losses during this period are listed in **Table 10.12.**

Table 10.12. Representative vessels lost during the Depression and New Deal (1930 to 1940).

Name	Date	Location	Circumstance	Country of Origin/ Type of Vessel
W. J. Colle	1930	Key West	Foundered	/Schooner
Rosemary	1930	Key West	Burned	/Schooner
Unknown	1930	Key West	–	–
Rubylee	1930	Olympia	Foundered	/Gas yacht
Amos Watchilt	1930	Key West	–	–
Captain Fritz	1930	Cedar Treet	Burned	/Steam sternwheel
Hiawatha	1931	Eastport	Burned	/Oil screw
Unknown	1931	Delta Shoals	–	–
65	1932	Phillip Inlet	Foundered	
Unknown	1932	Tavernier Key	–	–
Unknown	1932	Delta Shoals	–	–
Hilton	1937	Carysfort Reef	Stranded	/Gas screw
E. J. Bullock	1938	Dry Tortugas	Foundered	/Steam sternwheel
E. J. Bullock	1938	Dry Tortugas	Foundered	/Steamship
Venetia	1939	Ft. Myers	Burned	/Gas yacht
Caroline	1939	Cumberland Sound	Foundered	/Oil screw
3-R	1940	Content Keys	Burned	/Gas screw

World War II and Aftermath (1941 to 1949)

During World War II, Florida became one of the Nation's major training grounds for Army, Air Force, and Navy personnel. Several training centers were constructed and Key West was returned to active service as a naval base. Also at this time, coastal defense became a major consideration. German U-boats lurked in the Gulf Stream off the Florida coast, preying on enemy shipping. Sinkings were frequent events. The Civil Air Patrol, the Coastal Picket Patrol, and a hodgepodge of craft ranging from pleasure boats to dirigibles maintained a submarine watch. Shipbuilding became the State's principal industry, with much of this activity concentrated in Tampa Bay, Andrews Bay, and the St. Johns River. Florida emerged from the war with a strong economy, of which tourism quickly became the dominant component (Florida Department of State, Division of Historical Resources in prep.). Representative vessel losses are listed in **Table 10.13.**

Table 10.13. Representative vessels lost during World War II and Aftermath (1941 to 1949).

Name	Date	Location	Circumstance	Country of Origin/ Type of Vessel
Loice L	1947	Key West	Foundered	/Oil screw
Barbara	1948	Key West	Hurricane	/Gas screw
Avis G. Abel	1949	Key West	Burned	/Gas screw
Icacos	1949	Key West	Burned	/Gas screw

The Development of Commerce and Industry in the Florida Keys

The maritime history presented below highlights the importance of Key West as a port. Prior to the completion of the railroad bridge (and later, highway) connecting Key West with the Florida mainland, all of the transport into and out of the area was by ship. The heavy marine traffic and the hazardous reefs and shoals of the Florida Keys explain the presence of numerous shipwrecks in the area.

Throughout the historical period, Key West has attracted vessels like a magnet. For example, the noted English cartographer Bernard Romans, who published detailed sailing directions involving navigation through and within the Florida Keys in the 1770s, mentioned Key West (then *Cayo Hueso*), as a good watering point for vessels and indicated that "small deer" were available as a source of fresh meat for passing vessels (Romans 1775).

The following description of historical commercial and industrial shipping, as well as related onshore activities, has identified the potential for a rich archeological record on the inner continental shelf. At the same time this analysis provides the foundation for our understanding of the nature and distribution of these classes of cultural properties.

Shipping. Though initially settled as a military outpost, Key West's potential developed with surprising rapidity. On 7 May 1822, Congress established Key West as a port of entry. Soon thereafter, it became one of the most important transshipment points for flour and other commodities destined for Cuba. In 1826, 197 vessels (30 foreign, 167 American) entered the Port of Key West. Of these latter, 154 arrived from foreign ports. Also that year, 208 vessels (27 foreign, 181 American) cleared the port, including 151 destined for foreign ports. In December, 1827, the tonnage of Key West itself amounted to 1,223 vessels registered, and 59 enrolled. Imports for the year 1828 were reported as $164,446, with exports of $118,520.

By 1835, the number of vessels arriving and departing Key West had grown significantly. In that year, 331 vessels (10 foreign, 321 American) entered, while clearances numbered 260 (12 foreign, 248 American).

After the Civil War, Key West continued to grow in importance. By 1874, imports totaled $660,432. In 1876, 227 U.S. vessels arrived in Key West, including 153 steamers, 66 schooners, 5 brigs, 2 barks, and 1 ship. Three hundred sixty-five foreign vessels also made port at Key West, including 52 steamers, 266 schooners, 26 sloops, 12 barks, 7 brigs, and 2 ships. U.S. vessels clearing port numbered 221 (155 steamers, 52 schooners, 7 barks, 6 brigs, and 1 ship), while 350 foreign vessels cleared the port (60 steamers, 258 schooners, 26 sloops, 2 barks, 2 brigs, and 2 ships).

In 1888, in response to a yellow fever epidemic, the Senate Committee on Epidemic Diseases recommended the establishment of a quarantine station near Key West, "on account of the rapidly growing commerce with Cuba, the West Indies, and the Central American ports, nearly all of which are more or less constantly afflicted with yellow fever" (U.S. Congress, Senate 1888).

Commercial shipping through Key West continued to grow through the 20th century. Imports for 1914 totaled $1,293,683, while exports amounted to $747,346. Noncoastal vessels entering the harbor numbered 626. Clearances for noncoastal vessels totaled 601. The post-World War I years brought rapid growth to the island. By 1920, imports had reached $7,214,730. Exports had soared to $62,676,788. In that year, noncoastal vessels arriving in port numbered 1,144; while 1,111 vessels cleared Key West for foreign ports (Maloney 1876; *History of Florida Past and Present* 1923).

Shipbuilding. Key West also developed its own shipbuilding industry, and by 1853 had its own marine railway. By 1878, over 2,000 vessels of up to 519 tons were serviced. Between 1835 and 1876, 31 vessels were built in Key West for local owners. These were primarily schooners and sloops, ranging from 5 to 171 tons. However, one large vessel, the clipper ship *Stephen R. Mallory* (of 980 tons and built of mahogany) was launched in 1855. This two-deck, round-stern "clipper," built by Bahamian John Bartlum, was 50 m long, 11 m in beam, with a depth of hold of 5.4 m, and was fastened with iron and copper. In the years before the Civil War, the *Mallory* traveled from New York to San Francisco and from London to New York. The vessel continued to operate under Key West ownership until 1864, when she was sold in London (U.S. Congress, Senate 1830; Maloney 1876; Mueller 1967). Undoubtedly, a variety of small craft were constructed locally throughout the islands' history as well.

Commercial Fishing. With its extensive coastline, South Florida has always enjoyed a thriving fishing industry. From about the mid 18th century, fishermen from Cuba frequented both the Atlantic and Gulf coasts of South Florida and the Florida Keys. These hardy souls, who often came in family groups aboard sizable sloops, sometimes established semipermanent camps on the higher keys, where they caught and salted their catches for export to Cuba. Another important export not commonly reported during this period was oil rendered from the fat of the docile marine mammals called manatees (Covington 1954).

After Florida became a U.S. territory, American settlers began to occupy locations in the Florida Keys. Remote from the growing troubles with the Seminole in North Central and Central Florida, which were destined to erupt into the Second Seminole War (1835 to 1842), the Keys were considered relatively safe and settlement there preceded that in most of the peninsula.

As a result of the Keys' proximity to thousands of square kilometers of shallows teaming with an extraordinary variety of marine life, fishing, although initially a subsistence activity, shortly developed major economic importance. By 1828, some 780 tons of local shipping was involved in the fishing industry and over $100,000 worth of fish a year were exported to Havana.

The bottom-fishing fleet of 1895 consisted mostly of 2- to 3-ton smacks equipped with open wells to keep the fish alive for market. Ninety-one boats, including five schooners and employing over 100 persons, were engaged in bottom fishing in Key West and the Lower Keys in 1895. This fleet produced a catch of 737 tons valued at $58,901 that year.

Sponge Fishing. Commercial sponging began in Key West before 1849. Initially, good sponging grounds could be found from the Marquesas all the way northward to Cape Florida and Biscayne Bay. After 1850, at least 150 schooners were involved in sponging along the coast north of Soldier Key while almost 200 smaller vessels were reportedly working beds around Key West in 1895. The larger vessels tended to work Gulf waters, while the smaller stayed mainly in the Florida Keys and Southeast Florida coast area.

By 1888, many of the shallower sponge beds had been depleted by overuse, and poling sponges up from greater depths was difficult. In the early years, 1,000 to 1,800 bunches might be brought in from a single trip, but by 1895, 500 bunches were considered a good harvest. In 1896, a hurricane caused the loss of at least 17 sponging vessels. By the turn of the century, Tarpon Springs had replaced Key West as the center of the Florida sponge fishing industry (U.S. Congress, Senate 1897; *History of Florida Past and Present* 1923; Shubow 1969).

The Wrecking Industry. The tremendous number of vessels plying the Straits of Florida gave rise to Florida's earliest, and, during the first half of the 19th century, largest and most infamous industry--wrecking. Local inhabitants were on constant watch for vessels wrecked on shoals or reefs. In such an event, the cargo, portions of the ship, or even the entire vessel might be claimed by eager "wreckers." Recovered goods were often written off as losses by the ships' owners. Before Key West became a port of entry in the 1820s, wrecks and cargoes recovered in South Florida were generally taken to Nassau or Havana for adjudication. However, in 1826, the U.S. Congress enacted legislation requiring that all salvage claims within American waters be brought to a U.S. port for settlement.

At first, most wrecking cases were transferred to St. Augustine on the upper Florida East Coast but in 1828, Congress established a Southern Judicial District seated at Key West. The settlement rapidly developed into the center of the "wrecking industry." In 1834, an observer noted that, "every person resident on the island is engaged in one out of only two occupations: he is either a Government officer, or he is a wrecker" (Tebeau 1960).

Between 1848 and 1859, 618 vessels, carrying cargoes valued at $22 million, were damaged off the coast of Florida. However, by the mid 1850s, government-built lighthouses were having a positive effect as navigational aids. In addition, both actual and alleged excesses on the part of the wreckers gave rise to a variety of restrictive government regulations during this period. As a result, wrecking activity waned, though wrecking incidents continued sporadically until well into the 20th century (U.S. Congress, Senate 1838, 1839; Merrick 1941; Diddle 1946; Dodd 1948).

Agricultural Products. In a limited way, Key West and some of the keys to the north also contributed agricultural products to the local economy and, to a lesser extent, for export. For example, before the outbreak of the Second Seminole War (1835 to 1842), Dr. Henry Perrine experimented with over 200 different varieties of tropical plants, primarily fruits, in a nursery established on Indian Key near Key Largo. The experiment lapsed, but some of the species Perrine introduced still exist in the Florida Keys today, although they are not commercially grown.

Pineapples were one of the agricultural products that gained a foothold in the limited agricultural area available in the Florida Keys (as they did in many areas of Southwest and Southeast Florida) during the late 19th and early 20th centuries. Large pineapple fields were established on both Key Largo and Elliot Key, and the fruit was loaded from the beach on sloops for shipment directly to markets in Baltimore, New

York, and Boston. Although Cuban competition ended the pineapple boom, the fruit was grown commercially in the Keys until after the turn of the century.

By the late 1830s, several cigar factories had sprung up in Key West, utilizing Cuban immigrants and high-quality Cuban tobacco. By 1870, some 29 cigar factories, each with an average income of $62,415, and with an aggregate of over 2,000 employees, were in operation. The cigar enterprise was severely affected by a huge fire in 1886, which resulted in the shift of much of the industry to Tampa in Southwest Florida. Even so, cigar making contributed significantly to the local economy as late as 1923 (Maloney 1876; *History of Florida Past and Present* 1923; Cash 1948; White and Smiley 1959).

Factors Governing Shipwreck Occurrence in the Study Area

Previous studies of submerged cultural resources in the Gulf of Mexico and along the Atlantic coast have produced a number of conclusions regarding factors influencing shipwreck occurrence. Garrison et al. (1989) have attempted to recognize patterns based on actual shipwreck locations, shipping routes, and environmental conditions, particularly hurricanes. They identified a trend toward increased numbers of shipwrecks through time, as well as a correlation between shipwreck density and storm occurrence in the northern Gulf of Mexico. Significant hurricanes occurred in the Straits of Florida in 1551, 1554, 1622, 1623, 1634, 1641, 1644, 1695, 1720, 1733, 1780, 1835, 1846, 1876, 1894, 1896, 1893, 1906, 1909, 1910, 1916, 1919, and 1960. Many involved considerable damage and claimed a number of vessels. The Hurricane of 1622, for example, resulted in the loss of the galleon *La Margarita* and the *Nuestra Senora de Atocha* west of the Marquesas Keys, plus the *Nuestra Senora de Rosario* and several other vessels in the Dry Tortugas.

In 1695, the fourth-rate *Winchester* was lost near Key Largo. The hurricane of 1733 claimed 15 vessels in the Florida Keys. Garrison et al. (1989) have compiled a table of hurricane activity and losses in the northern Gulf of Mexico for the 16th, 17th, and 18th centuries.

The first officially recorded hurricane at Key West occurred on 15 to 17 September 1835, coincident with the appearance of Halley's Comet. Many vessels were wrecked on the reefs or otherwise damaged. The severe hurricane of 11 October 1846 wiped out a year's work on Fort Taylor. It also washed away the first lighthouse, and sent a house floating out to sea with someone still inside. The hurricane of 1896 dealt serious injury to Key West's sponging fleet. *Merchant Vessels of the United States* for 1909 records at least 25 registered vessels lost at Key West during the hurricane of 11 October of that year, including 16 schooners, 3 sloops, 3 gas screws, and 2 steamers. (This storm also destroyed several cigar factories and most of the island's churches, though the saloons survived unscathed.) Another hurricane the following year claimed at least 13 more registered vessels, including 10 schooners, 2 steamers, and 1 gas screw (U.S. Department of Commerce 1906-41; White and Smiley 1959).

A significant geographic factor controlling the location of shipwrecks identified by Garrison et al. (1989) was the Florida Keys themselves. The authors concluded that, "the convergence of winds, current, reefs, and storms, make the Straits of Florida the most hazardous area for ships that exit or enter the Gulf."

In 1887, Captain P. H. Hanlon of the Plant steamship *Mascotte* corresponded with Captain Black of the Army Corps of Engineers regarding Black's proposal to deepen the Northwest Channel at Key West. His letter offers a 19th-century shipmaster's view of the hazards of the Florida Keys:

"I am not prepared to state the number of vessels lost on the reefs west of Key West, but I know there has been many picked up on the west end of the Quick Sand and around where the Rebecca Light now stands, all the dangerous navigation of the reef from Key West to the Rebecca Channel, and the dangers of passing through the Rebecca would be avoided [by deepening the Northwest Channel]. The winds from northwest, around by west to south, produce fog, and what is called by the majority of seamen smoke. This smoke I have found to exist more thick the closer you go to the reefs, and also going through the Rebecca.... I also found the flood-tide to run north and sweep through the Boca Grande Channel, and also through the Rebecca."

"The effect of this tide is strongly felt on the outside of the reef, particularly when the wind is southwest, south, or southeast, which wind influences the Gulf current and blows it almost right on the reefs, making it impossible for any sailing vessel to sail close enough to keep out of current or make any headway in moderate weather. Another danger to sailing vessels in these waters must be taken into consideration; that is, the winds almost at all times die out at night and leaves them to the mercy of the tide. The current runs due east almost all year, but the northern winds in the spring blow it on the coast of Cuba. South and southwest winds blow it back on the Florida reefs" (U.S. Congress, House 1889b).

Previous Research and Predictive Models

The 1977 baseline study for historical resources on the northern Gulf of Mexico continental shelf developed a predictive model for shipwreck distributions within that region (Coastal Environments, Inc. 1977). It estimated a total population of 2,500 to 3,000 shipwrecks, at least 70% of which would date to 1800 or later. It further predicted that 80 to 90% of the total shipwreck population would be located within 10 km (5.4 nmi) of the Gulf coastline. Seventy to ninety percent of those vessels were expected to be found concentrated in a zone extending 1.5 km (0.8 nmi) from the coast. Finally, the 1977 study postulated a bell-shaped curve for shipwreck events, with a peak during the period 1880 to 1910.

Mistovich and Knight (1983) tested part of the 1977 predictive model against data compiled for a submerged cultural resources survey of Mobile Bay, Alabama. They estimated that their own shipwreck data represented 20% of the probable total for small merchant vessels, 5 to 10% of pleasure craft and small noncommercial vessels, and 50% of the total number of larger commercial shipwrecks which occurred in and around Mobile Bay through time. They concluded:

"These estimates imply a much larger potential shipwreck population than that suggested by Coastal Environments, Inc. ...who imply that their inventory (which included only 111 entries for the Mobile Bay area as compared to 282 in this one) is conservative by a factor of only 24 to 37%" (Mistovich and Knight 1983).

The revised baseline study for the northern Gulf of Mexico (Garrison et al. 1989) used statistical analysis on a computerized shipwreck data base to test the previous model. The 1989 wreck file contained more than 4,000 entries. While the authors recognized an unspecified level of underreporting, they did not estimate a total potential shipwreck population for the study area. Temporally, the results of the statistic analysis conflicted with the 1977 model. Rather than the bell-shaped curve predicted by Coastal Environments, Inc., Garrison et al. found an overall increase in the number of shipwrecks over time. They concluded:

> "This fact is somewhat surprising if one assumes, like the [Coastal Environments, Inc.] investigators, that improvements in the technology of ship design, the use of artificial motive power such as diesel or steam, and better navigational tools would reduce the number of ships lost over time. This statistic may be too general, and the rate of shipwrecks may be more indicative of the influence of improved technology. Improved technology may allow more vessels to be exposed to risks that early mariners would avoid because of recognized shortcomings in their ships or navigational aids" (Garrison et al. 1989).

Utilizing spatial distribution plots, the same authors determined that 75% of recorded shipwrecks within their study area were located in nearshore environments (ports, channels, coastal waters), with the remaining 25% occurring in the open sea. For nearshore environments, the study found that values for shipwrecks in port areas peaked during the 19th century. They attributed earlier losses to primitive navigation, storms, piracy, warfare, and a progressive increase in the number of ports through time. As an explanation for the continued frequency of nearshore shipwrecks through the 19th and 20th centuries, the authors speculated that "the categories of ports and bars may be an example of a mixed variable. An explanation of the frequency of shipwrecks may be the direct result of a ship coming to port where an entrance bar lies." For shipwrecks occurring in coastal waters, they concluded that "other bars such as longshore or off headlands are factors in explaining the occurrences of wrecks in shallow waters. Strandings are the result of encountering these hazards" (Garrison et al. 1989).

The distribution patterns for the remaining 25% of shipwrecks located in the open sea are "the result of economic decisions involving maritime commerce...[i.e., the use of specific shipping lanes]. As a determining cause in shipwreck patterns, winds and currents must be viewed as secondary" (Garrison et al. 1989).

There may also be a partial correlation between ports and hurricanes to explain the high frequency distributions of shipwrecks found in port areas by Garrison et al. (1989). With the advent of weather reports, shipmasters would have been forewarned and more of them would have had the opportunity to take refuge in protected harbors. Even so, many vessels in harbors were still lost to hurricanes. This may be a partial explanation for the continued concentration of shipwrecks in ports at later periods. Other contributing factors may have been scuttling, abandonment, and dockside fires.

The baseline study for the northeastern U.S (Roberts 1979) added another factor to the prediction of density and distribution of wrecks. This factor was the changing buoyancy of vessels over time. **Figure 10.2** illustrates the expected effect of all factors contributing to the density and distribution of wrecks over time. One caution is necessary, however. When using shoreline position and water depth to predict the location of wrecks, the models apply to the shoreline position and water depth *at the time of the sinking.* It has been demonstrated that ongoing coastal erosion through time may drastically alter coastlines and offshore water depths which in turn will influence the accuracy of prediction (Roberts 1985).

While the conclusions of the previous baseline studies regarding causal factors and distribution patterns follow the general line of common sense, there are some problems encountered in applying a broad-range shipwreck study to a specific area. The most basic difficulty is inherent in the data themselves. Recorded accounts of shipwrecks are highly variable in quantity, quality, and substance. For some classes of vessels, such as the Spanish treasure fleets, there has already been enough primary research to produce at least a couple of respectable wreck lists (see, for example, Marx 1975). Even so, locational data are still rather sketchy. Available shipwreck data for the southeastern

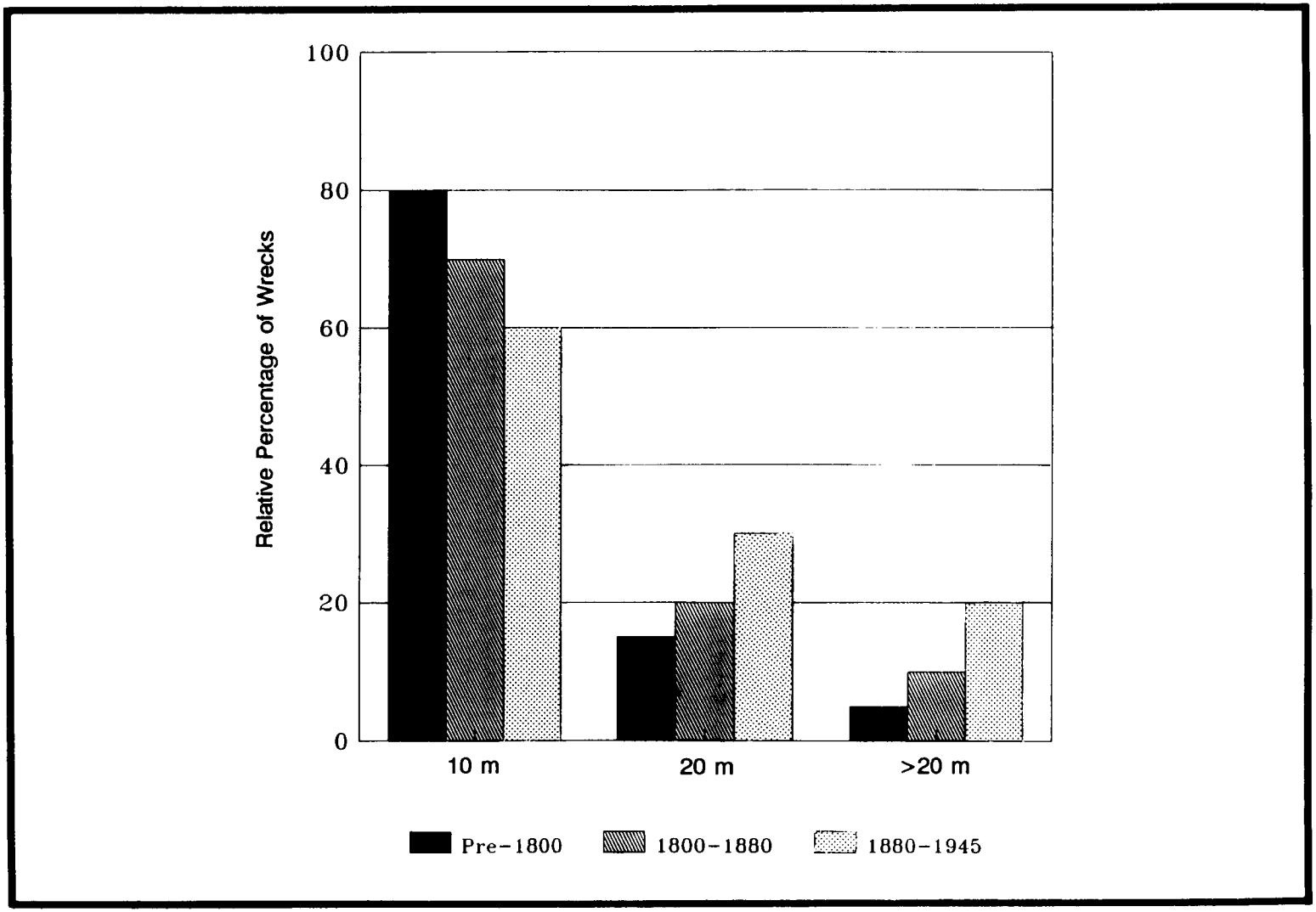

Figure 10.2. Expected relative wreck densities and distribution on the continental shelf, based on theoretical considerations (From: Roberts 1979).

U.S. appear to be generally skewed toward more recent larger commercial vessels, military craft (especially those of the Civil War period), steamboats, and in Florida, Spanish treasure ships. The data limitations noted by Mistovich and Knight (1983) for shipwrecks in Mobile Bay are generally applicable to coastal Florida as well:

> "It is undoubtedly deficient for small colonial craft and early sailing vessels, perhaps especially for pre-Civil War coastal fishing...craft. Pleasure boats of all periods are definitely under represented, as there are no rowboats, catboats, or skiffs in the compilation, and too few small yachts. Working craft too small for commercial registration do not make an adequate appearance."

While the lack of available data on local and small craft may not seriously retard statistical manipulations and generalized conclusions for larger areal studies, as the area gets smaller, the significance of this gap becomes progressively greater.

The fishing industry of the Florida Keys serves to illustrate additional problems of data and scale. In 1895, more than 400 fishing vessels operated out of the port of Key West alone, most of them sailing every day, year round. Yet quantitative and descriptive data on local fishing industries are hard to find; vessel-specific data are even more difficult. The exclusion of these vessels from submerged cultural resource management studies can result in a lopsided view of maritime activity, and thus of density of potential sites, within the study area.

Herein lies the problem of scale, however. The majority of fishing vessels operating out of the Florida Keys confined their cruising areas to those immediately off the Florida coast. Such a limited cruising range does not fit well into generalizations about shipping patterns in the northern Gulf of Mexico.

The data void created by the lack of information on small craft is intensified in coastal Florida. Until the completion of the Florida East Coast Railway in 1912, boats were as necessary to Key dwellers as today's family cars, and like them served the needs of both work and pleasure (Reiger 1971).

A final shortcoming in large areal studies of shipwreck occurrence is that they tend to focus on causal and locational factors that can be linked with established geographical patterns such as hurricane and sea currents. The value of such studies is not in question. There are, however, a number of other factors that have not received adequate attention. Vessel losses by explosion and burning fall into this category. Cultural factors, such as pirate attacks, abandonment, and intentional disposal also warrant further investigation. As with fishing vessels and other small craft, these might be better examined thematically, or within a more limited geographic area.

Survivability

The earliest systematic shipwreck investigations occurred in the late 1950s and early 1960s and focused on Classical sites in the Mediterranean Sea. The first archeological principles of site formation and shipwreck preservation therefore tended to dismiss the potential for significant shipwreck preservation in shallow, high-energy environments, directing archeologists instead toward deep sites with silty bottoms. Even today, after 30 years of archeological and historical research supported by remote sensing data and direct field observation, some archeologists still cling to the false idea that significant wreck remains do not survive in high-energy zones (Bass 1975; Muckelroy 1978; Agranat 1988).

Coastal Environments, Inc. (1977) identified six major factors relating to the preservation of shipwrecks: (1) sea state; (2) water depth; (3) bottom type; (4) nature of adjacent coast; (5) strength and direction of currents and waves; and (6) size and type of construction of vessel. They concluded that the distribution of wrecks of wooden vessels in shallow, reefy areas would follow the patterns of vessels lost on exposed coasts. Furthermore, "the distribution of wreck remains on broad, flat expanses of reef will generally greatly exceed those of a vessel lost on a reef with considerable variation in elevation." The study found that wrecks of steel vessels retained a higher degree of structural integrity than their wooden counterparts. They noted, however, that remains of any vessel that struck a reef, passed over, and settled into the relative shallow calm behind the reef might be less widely distributed.

Garrison et al. (1989) identified five classes of site preservation: (1) extensive structural remains; many organic remains and other objects in coherent distribution; (2) and (3) hull fragments, some organic and other objects, scattered distribution; (4) and (5) no hull, few to no remains, scattered, disordered distribution. They then compared archeological data from 18 wreck sites in the Gulf, Atlantic, and Caribbean. They found poorly preserved structural remains in 9 vessels sunk in high-energy, coarse-sediment environments, while organic remains were either absent or poorly preserved in 11 vessels in the same environment. Preservation of other objects varied widely and did not correlate with environmental factors. They also concluded that discontinuous wreck sites occurred only in high-energy environments, and that 19th-century wrecks are generally in better condition than those of earlier vessels. On the basis of an evaluation of environmental characteristics, the authors determined that the area encompassing the Florida Keys/Tortugas rated high for shipwreck potential, but low for preservation potential, for a moderate potential overall.

The question of the preservation of shipwrecks in high-energy zones is still being debated. Muckelroy (1978) has demonstrated that the potential for interpretation and reconstruction on "scrambled" sites far exceeds the limits generally perceived in the profession. The investigation of 8SL17, a surf-zone site on Florida's Atlantic coast concluded that, "...it is absolutely worthwhile and necessary to record both horizontal and vertical provenance. We are finding some differential vertical sorting but not nearly the horizontal movement expected if the common sense assumption holds correct" (Cockrell and Murphy 1978).

The variation of preservation from site to site is a result of chemical as well as physical processes. Those studies which have addressed re-sorting of artifacts on the seabed demonstrate that these processes and patterns of movement can be reconstructed on the basis of meticulous observation of conditions and documentation of finds. With proper recording and application of conservation techniques developed specifically for archeological materials recovered from underwater sites, significant contributions can be made to archeological study. As Steffy (1978) has pointed out, even a single structural fragment can be of immense value (see also Bass 1975; Cockrell and Murphy 1978; Muckelroy 1978; Agranat 1988).

With respect to wreck sites in low-energy zones, it has generally been considered an axiom in underwater archeology that the level of preservation of shipwrecks and associated artifacts increases with increasing depth and decreasing temperature. Often-cited examples of this phenomenon are the *Alvin Clark*, and the War of 1812 vessels *Hamilton* and *Scourge* in the Great Lakes. Observations of the remains of the *Titanic* since 1985, however, challenge this long-accepted notion:

"Only the great mass of the wreck had prevented a more complete destruction of the hull and superstructure. Expected redox rates due to low temperatures did not prevent the deterioration of the ferrous materials by biological and chemical factors. Certainly reduced or zero activity by one marine organism did not preclude the presence of another where the wood was concerned. Some of the more hallowed expectations concerning preservation in deep water shipwreck archeology were changed by early discoveries made on the *Titanic*" (Garrison et al. 1989).

More recently, a 17th-century Spanish galleon was discovered at a depth of 460 m off the Southwest Florida coast in May 1989 (*Tuscaloosa News*, 28 June 1989). The vessel appears to be intact with near-perfect preservation. Clearly, a generalization of wreck preservation processes in deep water would be premature at this time. Only through the systematic investigation of a variety of shipwreck sites in a variety of environments can archeologists hope to develop an overall theory of preservation processes.

Detectability and Recoverability

The location, identification, investigation, and interpretation of shipwreck sites is a systematic process. The location of shipwreck sites encompasses two separate, but complementary investigative techniques: historical research and field survey. The purpose of historical research is twofold. First, it provides an overview of human activity with the study area. Historical research may uncover patterns of cultural behavior that are indicative of potential shipwreck distributions. Examples are maritime trade routes and fishing grounds. Secondly, historical research can yield vessel-specific data on shipwreck events. Any investigation should begin with broad historic research, concentrating on secondary sources, followed by a more intensive examination of pertinent primary materials.

Surveys for submerged archeological resources are generally carried out using remote sensing technology. Occasionally, site conditions will preclude the use of such instruments. Geologic characteristics of the underlying bedrock, for example, can in some instances render a magnetometer survey entirely useless. For the most part, however, remote sensing offers the least expensive, most productive method for locating shipwreck sites. Three primary techniques are used in remote sensing surveys. The magnetometer detects changes in the magnetic field caused by ferrous objects, such as engines and hull fastenings, on the sea bottom. It cannot locate sites that lack ferrous components. Side-scan sonar uses acoustical waves to create terrain maps of the ocean bottom. Wrecks which protrude above the surface can be located using this method. Aerial survey and satellite imagery can also be of use in locating submerged sites, although they are dependent on visibility, wavelength, and scale. Lastly, remotely operated vehicles have proven particularly useful in locating shipwrecks in deepwater environments, beyond the reach of traditional methods. When equipped with video systems, they simulate first-hand observation of the ocean bottom. Navigational control is critical in remote sensing survey. Likewise, line spacing should be designed for maximum return, assuring adequate overlap. Remote sensing surveys generally yield a number of targets and/or magnetic anomalies. An analysis of the signal pattern may suggest an origin; however, *in situ* examination, whether by an archeologist or by a remote sensing device, is generally necessary to identify the object.

Once a shipwreck has been located, a near-field magnetometer survey may aid in delineating site dimensions. The application of remote sensing technology to the investigation of a single shipwreck site was pioneered by Clausen on a wreck off the east coast of Florida in 1965. That study concluded that, "The systematic survey of an

underwater historical period shipwreck site using an advanced proton-type magnetometer has permitted us to plot the distribution of the major ferrous components of the wrecked vessel *in situ*" (Clausen 1965). The technique was refined further by Clausen and Arnold (1976) on shipwrecks off the Texas coast. Controlled test excavations will yield valuable archeological data while keeping site disturbance to a minimum. Test excavations provide a representative sample of materials preserved at the site, from which an assessment of the relative condition of the vessel and associated artifacts can be drawn. Recovered materials may also offer clues to the identity, origin, and date of the vessel.

The investigation of shipwrecks in deepwater environments (i.e., beyond the limits for diving) requires that the archeologist complete all studies with remotely operated equipment. Video and photogrammetric surveys have already been accomplished on deepwater sites, as well as limited artifact sampling.

CULTURAL RESOURCE MANAGEMENT ISSUES

The foregoing analysis of existing information makes it clear that important elements of our National heritage do indeed lie on the continental shelf and that they can be detected and recovered with today's technology. While the concept of preservation in place is as valid for these resources as it is for terrestrial resources, there are forces at work that put these little-known sources of significant information and material at risk.

The management of offshore cultural resources requires a knowledge of the full range of potential resources as well as an understanding of threats to their integrity. Additional analytical studies as well as detailed studies taken in advance of planned offshore activities will significantly add to our knowledge of the shelf's resources. It is also currently possible to identify those activities that affect resources and thus plan for avoidance of the expected resources or develop programs to mitigate this effect.

There are two classes of issues to be addressed on the South Florida shelf at this time. The first is uncontrolled salvage of significant cultural resources, which instills urgency into the task of locating, evaluating, protecting, and preserving these elements of our past. The second is the potential effects of mineral extraction activities and their supporting infrastructure on the expected resource base. Concerns raised by the State of Florida with respect to the effects of oil and gas operations, including the hazards accompanying accidents such as oil spills, are included in the discussion below.

Uncontrolled Salvage and Vandalism of Cultural Resources

The development of scuba in the mid 20th century introduced a new threat to the shipwrecks in the Florida Keys. The Conference on Underwater Archeology and the Society for Historical Archeology have estimated that more than two million Americans belong to recreational diving community (U.S. Congress, Office of Technology Assessment 1986). A great many of these dive in Florida waters. The size of the tourist trade in the Florida Keys virtually guarantees that a number of foreign visitors also dive on Florida wrecks each year. While the potential for harm to an individual wreck site from a single sport diver may be comparatively low, the sheer numbers of divers visiting wrecks off the Florida coast annually has resulted in considerable attrition.

Though sport divers pose a threat to submerged cultural resources by their sheer numbers, the threat from organized treasure salvaging operations is much greater. The development of new remote sensing technology has greatly expanded access to

shipwrecks off the Florida coast. With the magnetometer, vast areas of ocean bottom can be surveyed from a boat with relative ease. Treasure salvagers have been particularly attracted to the gold-laden Spanish treasure wrecks of the 17th and 18th centuries. Arnold (1978, 1981) has identified three primary archeological principles that have traditionally been ignored, or minimized, by salvage operators: "Careful excavation, recording of provenance, and extensive conservation are to a treasure hunter a waste of time, and time is money" (Arnold 1981). Over the years, the State of Florida has developed programs and regulations for the commercial recovery of artifacts from the sea bed, aimed at minimizing the loss of archeological data through indiscriminate use of technology (see, for example, Burgess and Clausen 1976). The Florida Historic Resources Act of 1989 establishes policy and responsibilities for the stewardship of the State's historic and archeological resources. This act applies to resources within the underwater jurisdiction of the State.

Since 1979, there have been attempts to coordinate shipwreck preservation through legislation on the Federal level. Finally, in 1987, the U.S. Congress passed the Abandoned Shipwreck Act, which asserts public ownership of abandoned vessels in State waters and transfers responsibility for shipwrecks embedded in State bottomlands to the states. Title to warships and other publicly-owned vessels is retained by the Federal government. This legislation effectively removes shipwrecks in State waters from the jurisdiction of the Admiralty Courts and places them within the public trust (U.S. Congress, Office of Technology Assessment 1986; National Park Service [NPS] 1989).

The Abandoned Shipwreck Act also directed the NPS to develop and publish guidelines for State and Federal agencies to assist them in developing legislation and policies under the Act; "The Guidelines are intended to enhance cultural resources, foster a partnership among the interested groups, facilitate recreational access and use, and recognize the interests of those engaged in shipwreck discovery or salvage" (NPS 1989).

Mineral Extraction Activities

According to **Chapter 11**, oil and gas development is the only mineral extraction activity currently anticipated for the continental shelf of the study area. Other exploitable resources such as phosphate deposits may exist offshore in the study area; however, there is no existing mining activity, and none is expected in the foreseeable future.

Dredging of offshore sand deposits for beach fill does occur in South Florida and has the potential for damage to submerged cultural resources. The extraction of sand and gravel for a variety of purposes removes the protective sediment from those drowned features that are used as predictors of prehistoric-resource location, and from buried sites themselves. This action not only exposes previously protected sites to the forces of current and storm (an indirect effect) but may directly damage or remove the sites themselves. In addition, many lost vessels are buried in bottom sediments and thus may be damaged by the extraction process.

The primary sources of threat to prehistoric and historic resources are physical damage or loss of integrity through mechanical processes and modification of the existing preservation regime through a change in the chemistry of the matrix within which the resource exists. Effects of mechanical processes may be limited or even disregarded if the protecting sediment is not disturbed. On the South Florida continental shelf, however, the thickness of the sediment is highly variable and can be locally very thin or nonexistent. Thus, planned activities must be closely evaluated within their local zones on a case-by-case basis.

There are many activities that accompany the exploration, development, and production of oil and gas resources on the shelf. **Table 10.14** lists potential effects of these activities on archeological resources. This information is adapted from the management volume of the baseline study of the northeastern U.S. continental shelf (Roberts 1979). Activities such as rig, platform, and pipeline fabrication, and refinery construction and operation are omitted, because these would not be conducted in the study area (see **Chapter 12**). Construction and operation of an onshore service base in the study area is considered unlikely, but is included for completeness. (See **Chapter 12** for more information on the scope of offshore oil and gas operations and an overview of environmental consequences).

The table illustrates the fact that oil and gas operations can affect cultural resources in a variety of ways, not the least of which is the positive effect of discovery when it occurs in the course of implementing standard MMS procedures during the several phases of oil and gas operations (MMS 1986). These procedures are fully described in the MMS *Handbook for Archaeological Resource Protection (620.1-H)* as well as the pertinent Notices to Lessees (NTLs) and Letters to Lessees (LTLs) for the Atlantic and Gulf of Mexico OCS Regions.

The Florida Department of State, Division of Historical Resources (1989) presented a position statement entitled *Historic Preservation Issues Response to Proposed Oil and Gas Drilling off Florida's Coast* at a Presidential Outer Continental Shelf Leasing and Development Task Force workshop in June 1989. This statement identified two levels of concern: (1) direct and indirect effects of exploration activities; and (2) direct and indirect effects of production activities.

The discussion of these concerns identifies many of the hazards to historic and archeological resources noted above in the assessment of oil and gas development effects. Direct effects may be either mechanical or chemical and include the petrochemically-induced modification of radiocarbon datability, as well as the modification of a preserving anaerobic environment and thus the destruction of a regime within which extremely significant materials can be expected to exist intact. Potential indirect effects of both exploration and production could include damage done to the inshore environment by oil spills and other chemical releases, which may in turn affect site-protecting flora common along the mainland shoreline of the study area. The Division of Historical Resources offers its cooperation to Federal managers and others charged with evaluating the effects of specific actions on currently known resources and those areas were unknown resources can be expected to exist (Florida Department of State, Division of Historical Resources 1989).

The Division cautions that significant historic and archeological resources will be adversely affected by oil and gas activities if the appropriate studies are not undertaken and if, as a consequence of such studies, project activities are not modified to avoid or mitigate adverse effects upon these resources. In addition, if measures are not taken to prevent or promptly contain oil spills, there may also be adverse effects to significant resources.

Table 10.14. Potential effects of oil and gas operations on archeological resources (Adapted from: Roberts 1979).

Operational Phase	Activity/Technology Used	Pollutant/Agent	Archeological Effects
1. Geophysical/ Evaluation	A. Seismic Surveying	A. Noise from sparkers, acoustic equipment	A. Positive: may result in site location
	B. Bottom sampling (1) Coring (2) Dredging	B. Disturbed sediments	B. Negative: will disturb resurface and buried resources; Positive: may result in site location
2. Exploration	A. Rig fabrication	A. N/A in study area	A. N/A in study area
	B. Rig emplacement	B. Rig location	B.
	Anchoring and installation	(1) Disturbed surface sediments (2) Disturbed subbottom sediments	(1) Disturb surface resources (2) Disturb buried resources
	C. Drilling	C. Routine discharges of drilling fluids and cuttings	C. Site burial, site destruction through chemical activity
	D. Temporary rig servicing (1) Logistic bases (2) Service craft	D. Construction of facility	D. Waterfront land use = site destruction
3. Development	A. Platform fabrication	A. N/A in study area	A. N/A in study area
	B. Platform installation	B. (Same as 2.B. above)	B. (Same as 2.B. above)
	C. Drilling	C. (Same as 2.C. above)	C. (Same as 2.C. above)
	D. Completion--installation of "Christmas tree," riser, and flow lines, and connection of wellhead to flow lines	D. Oil and petroleum compounds	D. Chemical effects to C-14 dating, historic shipping (asphalting) and chemical modification of surface soils
		Risers, connections, flow lines	Disturb surface sites
	E. Platform servicing (1) Permanent logistic bases (2) Service craft	E. (Same as 2.D. above)	F. (Same as 2.D. above)
4. Production	A. Separation of oil/water oil/gas, and scrubbing	A. Refinery location (onshore) Routine discharges of produced water (at sea)	A. N/A in study area Chemical effects to C-14 dating; chemical modification of surface soils
	B. Workover	B. (Same as 2.C. and 3.D. above)	B. (Same as 2.C. and 3.D. above)
	C. Improved recovery (1) Fracturing (2) High pressure reinjection (3) Water/detergent flooding (4) Polymer floating (5) Thermal techniques	C. Chemical residues	C. Chemical modification of sites
5. Transportation	A. Fabrication of transportation and/or storage facilities	A. N/A in study area	A. N/A in study area
	B. Storage facility emplacement at sea or onshore	B. Storage facility location	B. At sea: surface site disturbance; onshore: N/A in study area
	C. Transfer to tankers/ barges	C. Chronic oil discharge from tank cleaning and bilge pumping.	C. (Same as 3.D. above)
	D. Construction and emplacement of pumping facilities	D. Pumping facility location	D. N/A in study area
	E. Routine tanker/barge operations	E. (Same as 5.C. above)	E. (Same as 5.C. above)
	F. Pipeline fabrication and emplacement	F. Pipeline fabrication	F. N/A in study area
		Pipeline placement	Surface site disturbance
	G. Pipeline operations	G. Oil leakage, spills	G. (Same as 3.D. above)
6. Refining	A. Construction or expansion	A. Refinery location	A. N/A in study area
	B. Processing	B. Refinery emissions and waste disposal	B. N/A in study area

The MMS has established program policies regarding cultural resources (MMS 1986). The policies as stated are as follows:

- Consider the impacts on archeological resources in all aspects of planning, leasing, permitting, and regulatory decisions.
- Ensure that archeological resources are not damaged or destroyed by operations on the OCS.
- Achieve and maintain a consistent application of archeological resource stipulations, regulations, and other related requirements.

Procedures for implementing these policies are contained in the MMS *Handbook for Archaeological Resource Protection (620.1-H)*. This handbook also establishes the requirement for consultation with the State Historic Preservation Officer at all stages of the development process. This handbook and the commitment of the MMS to cultural resource protection seem to answer the concerns of the State about direct effects of oil and gas operations. However, there are no procedures for the consideration of cultural resources that may be affected by oil spills and subsequent cleanup operations. In addition, it will be important for the State and the MMS to collaborate on the establishment of more detailed procedures for physical testing of zones of expected resources (especially the use of coring, diver inspection, and test dredging), site evaluation, and data recovery well in advance of operations.

CONCLUSIONS

This summary and analysis of cultural resource information for the South Florida continental shelf has led to the identification of a number of findings about historic and prehistoric resources in the study area. It has also revealed gaps in the available information that limits the analysis of this information at this time. A review of these gaps allows us to identify several studies that will help to fill the gaps. In addition, existing oil and gas procedures such as shallow hazard analysis, have been reviewed and analyzed for the purpose of identifying opportunities to fill data gaps when they are conducted.

Prehistoric Cultural Resources

Intact, significant, prehistoric archeological resources exist in the study area. It is unlikely that these resources will be found in waters deeper than 50 m.

There are two discrete zones of drowned prehistoric cultural resource potential on the South Florida continental shelf: the Southwest Florida zone, and the Florida Keys zone. The model of prehistoric settlement location presented in this chapter is based on assessment of specific environmental factors, notably Holocene transgression, water table, and types and distribution of productive ecosystems, as they change through time. The model predicts that prehistoric archeological sites on the inner continental shelf are associated with specific topographic indicators that in most instances are readily detectable. These topographic indicators are (1) the 50-m bathymetric contour, (2) karstic features, (3) drowned stream channels, (4) drowned coastal features, and (5) outcrops of knappable lithic raw materials. These topographic indicators are differentially distributed through the study area, and the two subregions defined in this chapter (Southwest Florida and the Florida Keys) reflect these differences, as well as disparate effects of Holocene transgression and subsequent sedimentation on site preservation and detection. This analysis concludes that the frequency, preservation, and

potential for detection of prehistoric sites is higher on the inner shelf off the Southwest Florida coast than off the Florida Keys.

Other significant findings from this analysis are the following:

- Prehistoric archeological resources representing periods with few terrestrial parallels will exist in the study area.
- The preservation of otherwise perishable materials will often be much greater in submerged protected environments than terrestrial environments.
- The discovery and documentation of drowned prehistoric archeological resources will advance the accuracy of locational models.

Lost Vessels

The Straits of Florida and the Florida Keys have long been recognized as navigationally hazardous. The hazards are reflected in a diverse population of lost vessels representing various historical periods. Lost vessels of all periods can be found throughout the continental shelf; however, more vessels tend to be found in shallow water. Locations of lost vessels can be predicted through the location of submerged topography.

Lost vessels of the prehistoric and protohistoric periods may exist on the continental shelf, though none have yet been located. Because the prediction of the location of these lost vessels is extremely difficult given our current state of knowledge, operations on the shelf must be prepared for chance encounters.

Lost vessels of the 19th and 20th centuries appear to be greater in number and seem to be better preserved than those of other centuries. This notion should be evaluated in a systematic way.

Lost vessels in high-energy environments have research value and are as worthy of consideration under cultural resource management guidelines as those in more protective low-energy environments.

Cultural Resource Management

The MMS has procedures in place for the consideration of cultural resources at all stages of oil and gas development. These procedures include NTLs and LTLs for cultural resource surveys, in-house review of all cultural resource reports, and the *Handbook for Archaeological Resource Protection (620.1-H)*. The following measures could help to preserve and protect submerged cultural resources in the study area in the event that offshore oil and gas operations proceed:

- The MMS should work with the State of Florida to develop detailed procedures for the exploration for, reporting of, evaluation of, and data recovery from archeological sites, including the use of direct bottom examination, core samples, and test dredging.

- Survey line spacing for historic cultural resources should be evaluated to ensure detection of older wooden vessels and less ferrous concentrations of historic period material in the study area. The MMS Gulf of Mexico OCS Region has a new NTL in preparation that would reduce required survey line spacing from 150 m to 50 m, based on the findings of the Garrison et al. (1989) study (M. Stright, pers. comm. 1990, MMS). A similar requirement would be appropriate for the Straits of Florida Planning Area.

- The State of Florida's *Comprehensive Historic Preservation Plan* (currently in draft) should become an integral component of the management of cultural resources on the South Florida shelf.

- There are currently no procedures, policies, or joint working agreements in place to deal with the effects of oil or chemical spills on cultural resources. The State of Florida should identify for the MMS those coastal zones which have a high probability for containing significant cultural resources. The State of Florida and the MMS should develop joint working agreements, procedures, and policies for handling oil and chemical spills which may affect cultural resources.

- The NPS has developed guidelines for State and Federal agencies for the protection of submerged cultural resources. These guidelines should be evaluated by the State of Florida for incorporation into existing procedures.

Information Gaps

The sea level curve for the Southwest Florida area needs localized refinement. The amplitude, rate, and periodicity of the Holocene marine transgression is understood in outline, but many uncertainties remain. The settlement model used in this study is predicated on transgression, inferred distribution of paleoecozones, topography, and cultural adaptive systems. The specificity and reliability of knowledge for all these factors in the study area is generally poor.

The precise nature of Paleoindian and Archaic adaptive strategies is very poorly known, especially for areas now inundated, but also for interior zones. A glaring gap in this respect for South Florida is the Early Archaic period, for which virtually nothing is known; but similar scarcity of knowledge applies to Paleoindian and Middle Archaic populations as well. As more archeological information becomes available from both regions, modelling of these adaptive strategies will become more precise.

Other significant information gaps include the following:

- Data for paleoenvironmental reconstruction for the shelf is weak and is generally an extrapolation from terrestrial settings.

- Information on prehistoric and protohistoric maritime trade patterns is weak.

- Information on historic period vernacular/domestic trade and transportation in the Florida Keys and Southwest Florida is weak to nonexistent.

- Information regarding day-to-day life in the historic period and its influence on maritime activity in the study area is weak.

- A number of the archeological and historic contexts in the State Plan need to be reinforced with information regarding maritime activities in the study area, most notably the British Period and Reconstruction.

- The cultural factors influencing wrecks are poorly understood.

Future Studies

It is clear that information regarding the nature and distribution of both drowned prehistoric resources and lost vessels on the South Florida continental shelf is inconsistent and limited. This imposes limits on the development of predictive models for habitability and survivability of both prehistoric resources and lost vessels. This limitation, in turn, requires that investigators take a conservative attitude to the analysis of specific units of the shelf. In other words, the unknowns of the process force analysts to look more carefully at every possible location that may have resource potential. Studies aimed at refining the predictive models would lead not only to a marked increase in our understanding of human use of the shelf, but would allow analysts in the future to perform project-specific assessments more cost efficiently.

Necessary studies include those that can be accomplished through library and archival research as well as those that require the mounting of field efforts to obtain data for analysis. As more archeological information becomes available from the region, the modelling of prehistoric adaptive strategies will become more precise. As part of this greater precision, however, the paleoenvironments to which prehistoric communities were adapted must be studied directly, using geomorphological, sedimentary, and biological approaches. While these kinds of studies are inherently worthwhile, they also help to refine the locatability of prehistoric sites of the types addressed in this chapter, and so will help reduce the future costs of offshore exploration.

The most glaring gaps in information from the historic period concern everyday life in the study area, especially with regard to transportation, commerce, and other topics related to the probable distribution of lost vessels. Library research, oral history, and other approaches should be used in studies that fill these gaps.

From the protohistoric and prehistoric periods, there is a great need for studies aimed at improving our understanding of aboriginal trade, resource exploitation, transportation, and other factors affecting the use of vessels from these periods.

REFERENCES CITED

Agranat, B. J. 1988. Shipwreck preservation in high energy environments: The potential for San Juan Harbor, Puerto Rico. Report prepared for SHPO's Office, San Juan by OSM Consultants, Inc., Moundville, AL.

Alberi, A. D. 1981. In the wake of the *Atocha*. In *Underwater archaeology: The challenge before us*, ed. G. Watts. San Marino, CA: Fathom Eight.

Anuskiewicz, R. 1988a. Preliminary archaeological investigations at Ray Hole Spring in the eastern Gulf of Mexico. *Fla. Anthropol.* 41:181-185.

Anuskiewicz, R. 1988b. Preliminary archaeological investigations at Ray Hole Spring. In *Proceedings of the Eighth Annual Gulf of Mexico Information Transfer Meeting 416-418*. OCS Study MMS 88-0035. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Arnold, J. B. III. 1978. Some thoughts on salvage law and historic preservation. *Int. J. Naut. Archaeol. Underwat. Explor.* 7.3:173-176.

Arnold, J. B. III. 1981. Rescue archaeology in submerged sites. Paper presented to the New World Conference on Rescue Archaeology, 11-16 January 1981, Quito, Ecuador.

Ballard, R. D., and E. Uchupi. 1970. Morphology and Quaternary history of the continental shelf of the Gulf Coast of the United States. *Bull. Mar. Sci.* 20:547-559.

Bass, G. F. 1975. *Archaeology beneath the sea*. Harper Colophon, New York.

Beriault, J., R. S. Carr, J. Stipp, R. Johnson, and J. Meeder. 1981. The archaeological salvage of the Bay West site, Collier County, Florida. *Fla. Anthropol.* 34:39-58.

Blackwelder, B., O. Pilkey, and J. Howard. 1979. Late Wisconsin sea levels in the southwest U.S. Atlantic shelf based on in-place shoreline indicators. *Science* 204:618-620.

Burgess, R. F., and C. J. Clausen. 1976. *Gold, galleons, and archaeology*. New York: Bobbs-Merrill.

Bush, P. 1982. *Predevelopment flow in the tertiary limestone aquifer, Southeastern United States: A regional analysis from digital modeling.* U. S. Geological Survey Water Resource Investigations, 82-905.
Camp, V. Jr. 1960. Captain Brannan's dilemma: Key West 1861. *Tequesta* 20:31-44.
Carr, R. 1986. Preliminary report on excavations at the Cutler Fossil Site (8 Da 2001) in southern Florida. *Fla. Anthropol.* 39:231-323.
Cash, W. T. 1948. The lower East Coast, 1870-1890. *Tequesta* 8:57-72.
Chappell, J. and B. Thom. 1977. Sea levels and coasts. In *Sunda and Suhul*, ed. J. Allen, J. Golson, and R. Jones, 275-291. London: Academic Press.
Clausen, C. J. 1965. *A 1715 Spanish treasure ship.* Contributions of the Florida State Museum, Social Sciences No. 12. Gainesville: Univ. Presses of Florida.
Clausen, C. J., and J. B. Arnold. 1976. The magnetometer and underwater archeology: Magnetic delineation of individual shipwreck sites, a new control technique. *Int. J. Naut. Archeol. Underwat. Explor.* 5.2:159-169.
Clausen, C. J., H. K. Brooks, and A. B. Wesolowsky. 1975. The early man site at Warm Mineral Springs, Florida. *J. Field Archeology* 2(3):191-213.
Clausen, C. J., A. D. Cohen, C. Emilliani, J. A. Holman, and J. J. Stipp. 1979. Little Salt Spring, Florida: A unique underwater site. *Science* 203:609-614.
Coastal Environments, Inc. 1977. *Cultural resources evaluation of the northern Gulf of Mexico continental shelf.* Report prepared for the Bureau of Land Management and National Park Service. New Orleans.
Coastal Environments, Inc. 1982. *Sedimentary studies of prehistoric archaeological sites: Criteria for the identification of submerged archaeological sites of the northern Gulf of Mexico Continental Shelf.* Contract No. C35003(79). Baton Rouge: U.S. Department of the Interior, National Park Service.
Coastal Environments, Inc. 1986. *Archaeological investigations on the outer continental shelf: A study within the Sabine River valley, offshore Louisiana and Texas.* OCS Study MMS 86-0119. New Orleans: U.S. Department of the Interior, Minerals Management Service.
Cockrell, W. A., and L. Murphy. 1978. 8SL17: Methodological approaches to a dual component marine site on the Florida Atlantic coast. In *Beneath the waters of time*, ed. J. B. Arnold III. Austin: Texas Antiquities Committee.
Corliss, C. J. 1953. Building the overseas railway to Key West. *Tequesta* 13:3-22.
Covington, J. W. 1954. A petition from some Latin-American fishermen, 1838. *Tequesta* 14:61-66.
Daniel, I., and M. Wisenbaker. 1987. *Harney Flats: A Florida Paleo-Indian site.* Farmingdale: Baywood Publishing.
Diddle, A. W. 1946. The adjudication of shipwrecking in Florida in 1831. *Tequesta* 6:44-49.
Dodd, D. 1948. Jacob Houseman of Indian Key. *Tequesta* 8:3-20.
Doran, G. 1988. A consideration of archaeological wetsites. In *Proceedings of the Eighth Annual Gulf of Mexico Information Transfer Meeting*, 402-412. OCS Study MMS 88-0035. New Orleans: U.S. Department of the Interior, Minerals Management Service.
Dunbar, J. 1988. Archaeological sites in the drowned Tertiary Karst region of the eastern Gulf of Mexico. *Fla. Anthropol.* 41:177-181.
Fairbridge, R. 1984. The Holocene sea level record in South Florida. In *Environments of South Florida: Present and past*, ed. P. Gleason, 427-436. Coral Gables: Miami Geol. Soc. Mem. No. 2.
Faught, M. 1988a. Inundated sites in the Apalachee Bay area of the eastern Gulf of Mexico. *Fla. Anthropol.* 41:185-190.
Faught, M. 1988b. Some archaeological sites in the Apalachee Bay of Florida. In *Proceedings of the Eight Annual Gulf of Mexico Information Transfer Meeting*, 414-416. OCS Study MMS 88-0035. New Orleans: U.S. Department of the Interior, Minerals Management Service.
Florida Department of State, Division of Historical Resources. 1989. Historic preservation issues response to oil and gas drilling off Florida's coast. Statement presented to the Presidential outer continental shelf leasing and development task force, 12 June 1989, Tallahassee, FL.
Florida Department of State, Division of Historical Resources. In preparation. *Florida's comprehensive historic preservation plan.* Tallahassee.
Garrison, E. G., C. P. Giammona, F. J. Kelly, A. R. Tripp, and G. A. Wolff. 1989. *An archaeological investigation to reevaluate Cultural Resource Management Zone 1 in the Gulf of Mexico and to provide an interpretative framework to characterize unidentified magnetic anomalies and side-scan sonar contacts. Historic shipwreck studies of the northern Gulf of Mexico.* Draft report prepared for the Minerals Management Service, Gulf of Mexico OCS Region, New Orleans.
Gleason, P., A. Cohen, W. Smith, H. K. Brooks, P. Stone, R. Goodrick, and W. Spackman 1984. The environmental significance of Holocene Sediments from the Everglades and saline tidal plain. In *Environments of South Florida: Present and past*, ed. P. Gleason, 297-351. Coral Gables: Miami Geol. Soc. Mem. No. 2.
Griffin, J. 1988. *The archaeology of Everglades National Park: A synthesis.* Tallahassee: U.S. Department of the Interior, National Park Service, Southeast Archaeological Center.
Griffin, J. 1989. Time and space in South Florida: A synthesis. *Fla. Anthropol.* 42:179-204.
Griswold, O. 1965. *The Florida Keys and the coral reef.* Miami: Graywood Press.
History of Florida past and present. 1923. Lewis Publishing, Chicago.
Hoffmeister, J. 1974. *Land from the sea: The geologic story of South Florida.* Coral Gables: Univ. of Miami Press.
Lind, A. 1969. *Coastal landforms of Cat Island, Bahamas.* Research Paper 122, Chicago: Univ. of Chicago Geography Department.
Long, D. 1968. Workers on relief, 1934-1938, in Key West. *Tequesta* 28:53-62.
Maloney, W. C. 1876. *A sketch of the history of Key West, Florida.* Gainesville: Univ. of Florida Press (Facsimile edition, 1968).
Marx, R. F. 1975. *Shipwrecks of the western hemisphere 1492-1825.* David McKay, New York.
Meltzer, D. 1989. Why don't we know when the first people came to North America? *American Antiquity* 54:471-490.
Merrick, G. E. 1941. Pre-Flagler influences on the lower Florida east coast. *Tequesta* 1:1-10.
Milliman, J. D., and K. O. Emery. 1968. Sea levels during the past 35,000 years. *Science* 162:1121-1123.
Minerals Management Service. 1986. *Handbook for archaeological resource protection (620.1-H).* New Orleans.
Minerals Management Service 1990. *Gulf of Mexico sales 131, 135, and 137: Central, Western, and Eastern Planning Areas. Draft environmental impact statement.* OCS EIS/EA MMS 90-0003. New Orleans.
Mistovich, T. S., and V. J. Knight, Jr. 1983. Cultural resources survey of Mobile Harbor, Alabama. Prepared for the U.S. Army Corps of Engineers, Mobile District. OSM Archaeological Consultants, Moundville, AL.

Morner, N. 1976. Eustatic changes during the last 8,000 years in view of radiocarbon calibration and new information from the Kattegatt region and other northwestern European coastal areas. *Palaeogeography, Palaeoclimatology, Palaeoecology* 19:63-88.
Morrison, S. E. 1974. *The European discovery of America: The southern voyages*. Oxford Univ. Press, New York.
Muckelroy, K. 1978. *Maritime archaeology*. Cambridge: Cambridge Univ. Press.
Mueller, E. A. 1967. Florida's clipper ship. *Tequesta* 27:3-6.
National Park Service. 1989. Abandoned Shipwreck Act guidelines: Proposed guidelines: Notice. Washington, DC.
Oceanprobe, Inc. 1988. Final project report for cultural resources magnetometer survey, Brevard County/Canaveral Harbor, Florida. Report prepared for the U.S. Army Corps of Engineers, Jacksonville District, Jacksonville, FL.
Priestly, H. I. 1928. *The Luna Papers*. Florida State Historical Society Publ. No. 8. DeLand.
Reiger, J. F., ed. 1971. Sailing in South Florida waters in the early 1880s, Part 1. *Tequesta* 31:43-66.
Robbin, D. 1984. A new Holocene sea level curve for the upper Florida Keys and Florida reef tract. In *Environments of South Florida: Present and Past*, ed. P. Gleason, 437-458. Coral Gables: Miami Geol. Soc. Mem. No. 2.
Roberts, M. 1979. *Summary and analysis of cultural resource information on the continental shelf from the Bay of Fundy to Cape Hatteras. Vol. 4, Management*. Report prepared for the U.S. Department of the Interior, Bureau of Land Management.
Romans, B. 1775. *A concise natural history of East and West Florida* (facsimile reproduction of 1775 edition published in 1962). Gainesville: Univ. of Florida Press.
Saunders, W. H. 1959. The wreck of Houseboat No. 4, October 1906. *Tequesta* 19:15-22.
Schellings, W. J. 1955. On blockade duty in Florida waters. *Tequesta* 15:55-72.
Scholl, D., F. Craighead, and M. Stuiver. 1969. Florida submergence curve revised: Its relation to sedimentation rates. *Science* 163:562-564.
Sheldon, E., and M. Cameron. 1976. Reconstruction of prehistoric environments: Warm Mineral Springs Project. *S.E. Archaeol. Conf. Bull.* 19:68-69.
Shinn, E., B. Lidz, J. Kindinger, J. Hudson, and R. Halley. 1989. *Reefs of Florida and the Dry Tortugas*. St. Petersburg: U.S. Geological Survey.
Shubow, D. 1969. Sponge fishing on Florida's east coast. *Tequesta* 29:3-16.
Steffy, J. R. 1978. Maximum results from minimum remains. In *Beneath the waters of time*, ed. J. B. Arnold III. Austin: Texas Antiquities Committee.
Stright, M. 1988. Inundated archaeological sites of the Florida coastal region: A regional overview. In *Proceedings of the Eighth Annual Gulf of Mexico Information Transfer Meeting*. OCS Study MMS 88-0035. New Orleans: U.S. Department of the Interior, Minerals Management Service.
Tebeau, C. W. 1960. Two opinions of Key West in 1834. *Tequesta* 20:45-50.
U.S. Congress, House. 1836. On the claims of the widows, children and other relatives of the officers and crew of the United States schooner Wild Cat, which vessel foundered at sea. Naval Affairs 591, 24th Cong., 1st sess.
U.S. Congress, House. 1889a. Harbor of Key West, Fla., H. Ex. Doc. 39, 51st Cong., 1st sess.
U.S. Congress, House. 1889b. Northwest Passage, Key West Harbor, Florida. H. Ex. Doc. 145, 50th Cong., 2nd sess.
U.S. Congress, House. 1904. Key West Harbor, Florida. H. Doc. 567, 58th Cong., 2nd sess.
U.S. Congress, House. 1908. To remove certain obstructions to navigation from main ship channel of Key West Harbor, Florida. H. Rp. 1702, 60th Cong., 1st sess.
U.S. Congress, Office of Technology Assessment. 1986. *Technologies for underwater archaeology and maritime preservation*. Washington, DC: U.S. Government Printing Office.
U.S. Congress, Senate. 1830. Message from the President of the United States, with a report from the officers detailed to make a survey of the Dry Tortugas, and recommending it as an important station for Naval purposes & c., S. Doc. 111, 21st Cong., 1st sess.
U.S. Congress, Senate. 1836. On the importance and fitness of the Dry Tortugas as a harbor and station for the vessels of the Navy. Naval Affairs 632, 24th Cong., 1st sess., American State Papers.
U.S. Congress, Senate. 1838. Petition of a number of merchants of Charleston, S. Carolina, praying establishment of a port of entry and the erection of a light-house at Indian Key, S. Doc. 54, 25th Cong., 3rd sess.
U.S. Congress, Senate. 1839. Memorial of masters of wrecking vessels, on the coast of Florida, opposed to the establishment of a port of entry at Indian Key, S. Doc. 255, 25th Cong., 3rd sess.
U.S. Congress, Senate. 1888. Letter from the Secretary of War, in response to Senate resolution of February 2, 1888, as to the amount of money required for improving the north-east channel near Key West, Fla. S. Ex. Doc. 74, 50th Cong., 1st sess.
U.S. Congress, Senate. 1897. The fish and fisheries of the coastal waters of Florida, S. Doc. 100, 54th Cong., 2nd sess.
U.S. Congress, Senate. 1908. Removal of obstructions from main ship channel, Key West Harbor, Fla. S. Rp. 424, 60th Cong., 1st sess.
U.S. Department of Commerce. 1906-41. *Merchant vessels of the United States*. Washington, DC: U.S. Government Printing Office.
Van Arman, J. 1984. South Florida's estuaries. In *Environments of South Florida: Past and Present*, ed. P. Gleason, 79-96. Coral Gables: Miami Geol. Soc. Mem. No. 2.
Watts, W. A. 1975. A Late Quaternary record of vegetation from Lake Annie, South-Central Florida. *Geology* 3:344-346.
Watts, W. A. 1980. The Quaternary vegetation history of the southeastern United States. *Ann. Rev. Ecol. Syst.* 11:387-409.
Weddle, R. 1985. *Spanish seas*. College Station, TX: Texas A&M Univ. Press.
White, L. V., and N. K. Smiley. 1959. *History of Key West*. St. Petersburg: Great Outdoors Publishing Co.
Widmer, R. J. 1986. *Prehistoric estuarine adaptation at the Solana Site, Charlotte County, Florida*. Florida Division of Archives, History, and Records Management, Bureau of Archaeological Research. Tallahassee.
Widmer, R. J. 1988. *The evolution of the Calusa: A nonagricultural chiefdom on the Southwest Florida coast*. Tuscaloosa: The Univ. of Alabama Press.
Williams, A. W. 1954. Stronghold of the Straits: Fort Zachary Taylor. *Tequesta* 14:3-24.
Worcester, D. E., and W. G. Schaeffer. 1956. *The growth and culture of Latin America*. New York: Oxford Univ. Press.

CHAPTER 11
SOCIOECONOMICS

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INTRODUCTION

The purpose of this chapter is to describe the social and economic setting of South Florida. This information provides a basis for evaluating the possible social and economic consequences of proposed offshore oil and gas leasing and development in the study area (see **Chapter 16**).

The chapter is organized into sections that address major topics. The first section presents demographic and economic data on various aspects of the three-county (Collier, Dade and Monroe) study area. Subsequent sections discuss land use, water resources, marine transportation and port facilities, and military operations offshore within the study area. The discussion then focuses on the industries most closely related to the marine resources of the study area: commercial and recreational fishing, recreation and

tourism, and offshore minerals. Finally, the Federal and State parks, preserves and other areas of special concern in the study area are described and evaluated in terms of their importance for use and preservation.

POPULATION, DEMOGRAPHICS, AND EMPLOYMENT

The study area includes parts of three South Florida counties: Collier, Monroe, and Dade (**Figure 11.1**). Population, demographic, and employment statistics for each county, as well as for the three-county area are presented in **Tables 11.1 and 11.2.** In **Table 11.3** the population, demographic, and employment characteristics of the three-county area are compared with those of the State of Florida and the U.S.

Figure 11.2 shows the growth rate of the population of the three-county area between 1977 and 1987. **Table 11.1** provides information on 1980 and 1987 population, as well as projected population levels and rates of growth to 1990 and also to the year 2000. The most rapid population growth over the years 1980 to 1987 occurred in Collier County. Of the 67 counties in Florida, Collier County's population grew more rapidly than all but five (Florida Department of Commerce [FDC] 1988e).

Table 11.1. Population and demographics of Collier, Monroe, and Dade Counties (From: Bureau of Economic and Business Research 1988; Florida Department of Commerce 1988a,b,c,e).

Characteristic	County			Total
	Collier	Monroe	Dade	
Population in 1980	85,971	63,188	1,625,509	1,774,668
Population in 1987	126,631	74,523	1,802,427	2,003,581
Percent change 1980-1987	47.3	17.9	10.9	12.9
Projected population in 1990	144,150	79,563	1,859,932	2,083,645
Percent change 1987-1990	13.8	6.7	3.2	4.0
Projected population in 2000	192,400	88,127	1,989,046	2,269,573
Percent change 1987-2000	51.9	18.3	10.3	13.3
Population density/sq km in 1987	165	187	2,390	1,042
Age breakdown in 1987				
Percent 0 - 17	21.2	17.8	23.3	23.0
Percent 18 - 44	33.3	41.9	40.1	39.7
Percent 45 - 64	23.0	24.1	20.8	21.1
Percent 65+	22.5	16.2	15.8	16.2
Population share by sex in 1987				
Percent female	50.3	47.5	52.2	51.9
Racial composition in 1987				
Percent white	94.4	93.7	77.9	79.6
Registered voters in 1987				
Percent Democrat	29.2	60.6	57.9	55.9
Percent Republican	63.4	31.8	34.7	36.7
Percent other	7.4	7.5	7.4	7.4
Registered voters in 1987 as percent of voting age population	53.6	58.8	45.2	46.3

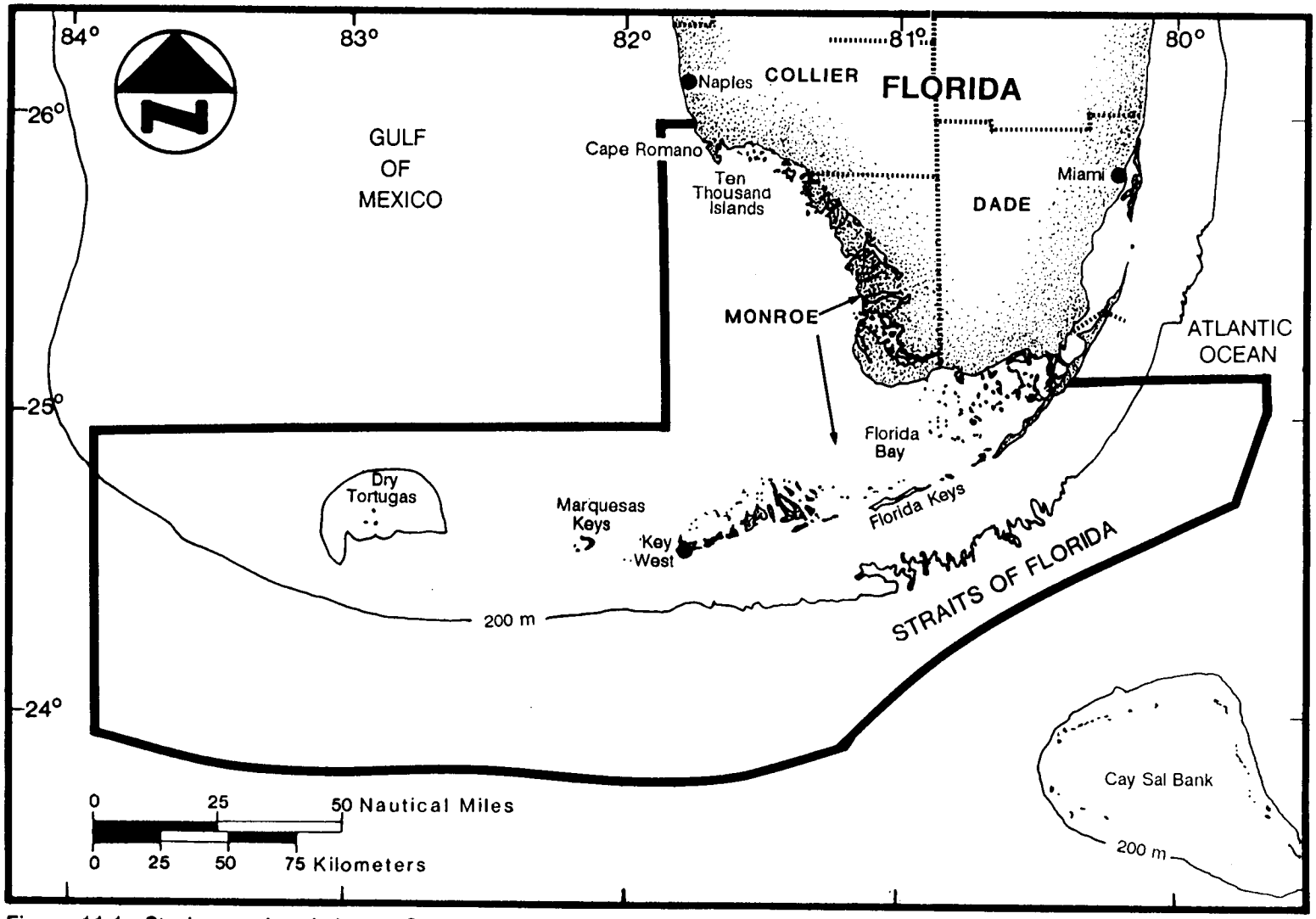

Figure 11.1. Study area in relation to Collier, Dade, and Monroe Counties.

Table 11.2. Employment statistics for Collier, Monroe, and Dade Counties (From: Bureau of Economic and Business Research 1988; Florida Department of Commerce 1988a,b,c,e).

Characteristic	County			Total
	Collier	Monroe	Dade	
Civilian labor force in 1980	36,088	28,490	815,818	880,396
Civilian labor force in 1987	60,742	42,455	913,179	1,016,376
Percent change 1980-1987	68.3	49.0	11.9	15.4
Unemployment rate (percent) in 1987	5.0	2.8	5.8	5.6
Labor force mobility (percent employed outside home county) in 1987	5.2	3.6	3.7	3.8
Per capita income in 1986	$18,402	$14,021	$14,863	$15,055
Percent change 1980-1986	50.4	57.2	45.2	45.8
Nonfarm employment in 1986				
Percent agricultural services	4.7	8.6	1.0	1.5
Percent mining	0.4	0.1	0.1	0.1
Percent trade	23.3	23.1	24.0	24.0
Percent trans-public utility	3.4	3.8	7.6	7.3
Percent manufacturing	3.1	2.1	9.6	8.9
Percent construction	11.4	6.6	5.2	5.6
Percent finance, insurance, and real estate	15.5	8.4	10.0	10.3
Percent services	30.0	28.0	30.9	30.8
Percent government	8.2	19.3	11.4	11.5

Table 11.3. Population, employment, and demographics for the three-county area, Florida, and the U.S. (From: Bureau of Economic and Business Research 1988; Florida Department of Commerce 1988a,b,c; Bureau of the Census 1989a).

Characteristic	Three-County Area	Florida	U.S.
Population in 1987	2,003,581	12,023,000	243,400,000
Projected population in 1990	2,083,645	12,818,000	249,891,000
Percent change 1987-1990	4.0	6.6	2.7
Population density/sq km in 1987	1,042	575	179
Age breakdown in 1987			
Percent 0-17	23.0	22.5	26.2
Percent 65+	16.2	17.7	12.1
Civilian labor force in 1987 (percent of U.S. total)	1.0	4.8	100
Civilian labor force			
Percent change 1980-1987	15.4	37.4	13.2
Unemployment rate in 1987	5.6	5.7	7.0
Per capita income in 1986	$15,055	$14,646	$14,641
Percent change 1980-1986	45.8	49.8	47.3

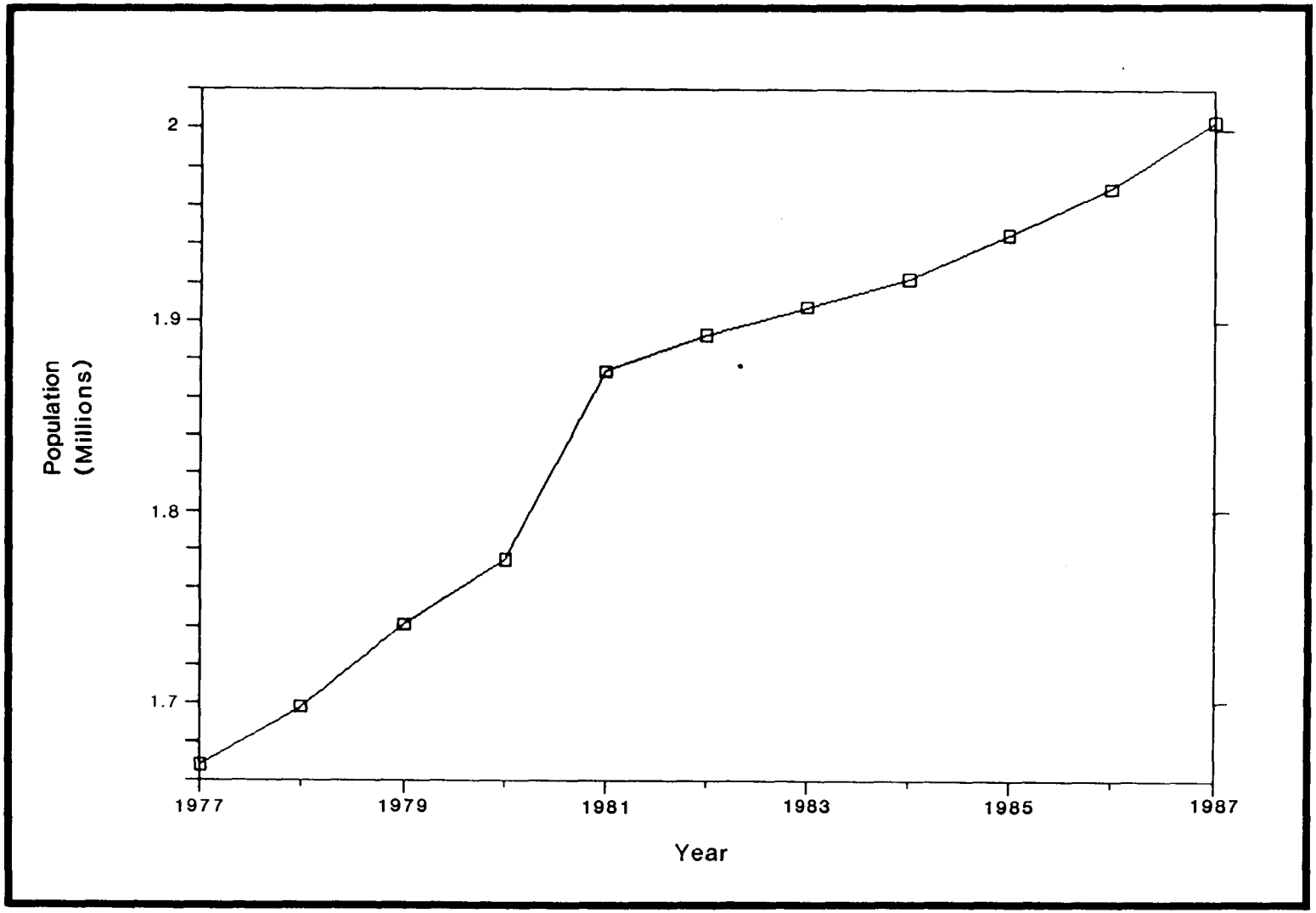

Figure 11.2. Population of the three-county area, 1977 to 1987 (From: Bureau of Economic and Business Research 1988).

The projected population growth rates for Collier County through the years 1990 and 2000 are more than twice as high as the three-county area and about twice as high as for the State of Florida as a whole. The expected population growth rate for the three-county area is more than 50% greater than for the U.S. Dade County, however, will grow more slowly than Monroe or Collier County, and also more slowly than the State of Florida as a whole.

Population density in Collier and Monroe Counties is much lower than in Dade County. Collier and Dade Counties have nearly identical land areas; Monroe County is somewhat smaller. But major portions of Collier County are included in the Fakahatchee Strand State Preserve and Big Cypress National Preserve, and most of Monroe County is made up of the Everglades National Park. Collier County's population is heavily concentrated along the northwestern coastline. Monroe County's population is concentrated in the Florida Keys, resulting in relatively high local population densities.

Much of the previous growth in South Florida, as well as anticipated future growth, is attributable to the in-migration of retirees. This is especially true for Collier County. The share of the population in the age group 65+ is significantly higher in Collier County than in Monroe and Dade Counties (**Table 11.1**). Collier County's 65+ population share is also significantly higher than that of Florida and nearly double that of the U.S. (**Table 11.3**). Dade County has also experienced large population growth due to in-migration (third highest in the State). These new entrants tend to be younger than new entrants to Collier County (FDC 1988e).

Not surprisingly, Florida leads the Nation in share of population in the oldest age group. Figures for the age groups "0 to 17" and "65+" for the State of Florida and the U.S. are presented in **Table 11.3**. As a result of the large population share 65 years of age and older, Florida has the smallest population share in the age bracket from 0 to 17 years for the 50 states. Florida also has the highest median age of any state, 36.3 years, as compared to the national average of 32.1 years (Bureau of the Census 1989b).

Breakdowns of population by gender indicate that a significantly larger share of the population is female in Dade County and a significantly smaller share is female in Monroe County (**Table 11.1**). For the three-county area, the percent of the population that is female is similar to that of the State and the Nation (**Table 11.3**).

The racial composition of Collier and Monroe Counties is similar, with both counties ranking high among Florida counties for percent white population (FDC 1988e). A much larger share of the population is nonwhite in Dade County (**Table 11.1**).

The final section of **Table 11.1** indicates that the political affiliation of registered voters in Monroe and Dade Counties is similar to that of the State and the Nation. Collier County voters choose the Democratic and Republican parties in percentages almost the reverse of Dade and Monroe Counties as well as the State and Nation. The category "registered voters as a share of voting age population" provides some evidence as to the level of political involvement of the local populations.

Table 11.2 presents information on the employment characteristics of the affected region. Both Collier and Monroe Counties have experienced dramatic increases in the size of their labor forces over the 1980 to 1987 period. While both counties also experienced rapid population growth over this same period, the Monroe County labor force grew at a rate more than double its population growth rate. The Collier County labor force grew about 50% faster than its population, while the Dade County labor

force grew at about the same rate as its population. While the Collier and Monroe County labor forces grew more rapidly than the State labor force, the slow growth of the Dade County labor force brought the three-county area rate of growth to a level far below that of the State but still slightly higher than that of the Nation (**Table 11.3**).

Unemployment data (**Tables 11.2 and 11.3**) indicate that Monroe County, with a 1987 unemployment rate of just 2.8%, has a very strong local economy. Unemployment rates in Collier and Dade Counties are much higher than in Monroe County. However, relative to the State of Florida and the U.S., unemployment in the three-county area is low.

Per capita incomes (1986) in Dade and Monroe Counties and in Florida are similar to the national average. Per capita income in Collier County is significantly higher. All three counties rank in the upper 25% of Florida counties on the basis of per capita income (FDC 1988e). The growth of per capita income for each county and the three-county area over the period 1980 to 1986 is similar to that of the State and the Nation.

Table 11.2 also presents data on the relative importance of various sectors of the local economies in the provision of jobs. Trade and services are the two strongest sectors accounting for more than 50% of all employment in each county.

The data presented here cover non-farm employment only. Information on employment in the fishing and shellfishing industries is grouped along with forestry and agricultural services under the "agricultural services" heading. Employment associated with the tourist industry is dispersed among the other categories and must be presented separately, as is done below.

Employment information for Florida counties is generally obtained from data reported by businesses whose employees are covered by unemployment compensation laws. Unfortunately, a large portion of the total fishing and shellfishing activity is undertaken by individuals and firms not subject to these reporting regulations. On the basis of survey data, Rockland (1988) estimated that the commercial fishing industry creates 1,190 jobs in Monroe County. Based on this approach, it may be estimated that 1,476 jobs are created throughout the three-county area by the commercial fishing industry (**Table 11.4**). The three-county estimate is based on the ratio of total ex-vessel fishery value yielded by the three counties together in comparison to Monroe County alone (the ratio is 1.37).

Estimates of employment in tourism-related industries, such as hotels and motels, eating and drinking establishments, and amusement and recreation services, are presented in **Table 11.5**.

Employment in tourism-related industries for Monroe County exceeds 20% of the local labor force, nearly double the State average. Collier County also has a larger employment share engaged in tourism-related industries than the State average but the Dade County share is significantly lower. Because of the size of the Dade County work force and that county's particular labor market characteristics, the share of the three-county area's total employment that is created by tourism-related businesses is actually below the State average.

Table 11.4. Commercial fisheries income and employment estimates (Adapted from: Rockland 1988).

	Income (thousands of 1987 dollars)	Employment (person-years)
Monroe County Fisheries		
Impact on Employment and Income in Monroe County	$14,828	1,190.5
Total Impact on Employment and Income in Florida	$51,682	4,932.5
Three-County Area Fisheries*		
Impact on Employment and Income in Three-County Area	$18,386	1,476.2
Total Impact on Employment and Income in Florida	$64,085	6,116.3

* The three-county estimates were derived by multiplying the Monroe County estimate by 1.37, which is the ratio of fishery landings in the three-county area to fishery landings in Monroe County alone.

Table 11.5. Tourism-related employment in 1987 (From: Bureau of Economic and Business Research 1988).

Area	Tourism-Related Employment	Percent of Labor Force
Collier County	9,206	15.2
Dade County	75,195	8.2
Monroe County	8,711	20.5
Three-County Area	93,112	9.2
Florida	564,291	11.3

In summary, the Monroe County economy is dependent on commercial and recreational fisheries and tourism-related businesses for a significant share (23.3%) of its employment (**Table 11.2**). Collier County employment patterns are more heavily weighted toward construction and financial services, both of which are dependent on the rapid population growth in that area. Dade County has a significantly larger fraction of its total employment generated by transportation, public utilities, and manufacturing industries. These patterns of employment reflect the metropolitan nature of the county and its high population density.

LAND USE

State and local agencies in Florida increasingly rely on land use management practices to provide balance against pressures for uncontrolled growth which might lead to environmental deterioration, loss of prime agricultural land, and destruction of watersheds and wildlife habitats. The need to control growth and to closely monitor the use of land resources is particularly vital in the South Florida region.

The special land use problems of the South Florida region arise from the nature of the land upon which the area is built. When the area was settled, most of South Florida was covered by marshes, swamps, or other wetlands. It was necessary to drain large amounts of water from these wetlands in order to make them amenable to development. As the area grew, more wetland areas were destroyed, and the value of remaining wetlands to the process of aquifer recharge and to the fisheries of the area became more apparent. As a consequence, the preservation of these wetlands has become a high priority. Growth management policies have had the effect of placing any remaining land that is suitable for development at a premium.

Land use management separates land uses into the categories of commercial, residential, agricultural, and public uses.

- **Commercial uses** are defined as lands having permanent structures which are predominantly connected with the sale of products and services. General commercial refers to retail sales, services, and professional service trades. Tourist services include all facilities which support hotels and motels. Industrial services consist of businesses involved in manufacture, assembly, and processing. These include commercial fishing and processing areas, oil and gas storage areas, and boat assembly plants. Religious buildings, cemeteries, golf courses, marinas, plant and tree nurseries, and privately owned medical facilities are also included in the commercial use category.

- **Residential uses** are divided into single family units, mobile homes, multifamily uses, and mixed. Residential uses are also divided according to density.

- **Agricultural uses** include traditional grain and vegetable crops, sugar cane, grazing, orchards, and dairies.

- **Public uses** refer to all land owned by a public entity such as Federal, State, and local governments. These include military installations, parks, public buildings, and schools.

Current land uses in the three-county area are described in **Tables 11.6 to 11.8.** About 96% of the land area in Collier County is undeveloped, most being environmentally sensitive wetlands. The small portion of Collier County that is currently developed (3.75%) is located along the coast. The land area of Monroe County is dominated by Everglades National Park and the Big Cypress National Preserve, which

Table 11.6. Land use in Collier County in 1988 (From: Collier County Growth Planning Department 1989).

Land Use	Percent of Total Land Area
Developed Lands	**3.75**
Urban Residential	2.56
Commercial and Services	0.11
Industrial	0.12
Institutional	0.06
Transportation	0.30
Open and Others	0.33
Under Development	0.27
Undeveloped-Environmentally Tolerant Lands	**24.55**
Undeveloped Urban	0.11
Agricultural	11.08
Rangeland	0.81
Forested	12.55
Undeveloped-Environmentally Sensitive Lands (wetlands)	**71.40**
Other Lands	**0.30**
Beaches	0.05
Extractive Resource Lands	0.18
Barren lands	0.07

Table 11.7. Land use in Monroe County in 1985 (From: Monroe County Board of County Commissioners 1986).

Land Use	Percent of Total Land Area
Everglades National Park (public and private)	**82.74**
Big Cypress National Preserve (public and private)	**11.08**
Offshore Islands (public and private)	**0.84**
Acreage Subject to Development	**5.33**
Built Residential	0.80
Built Government/Utilities	0.21
Built Commercial	0.19
Vacant	4.13

Table 11.8. Land use in Dade County in 1988 (From: Metro Dade County Planning Department 1988c).

Land Use	Percent of Total Land Area
Residential	**5.24**
Commercial	**0.57**
Hotels, Motels, and Other Transient Residential	**0.05**
Industrial	**0.92**
Extraction, Excavation, and Quarrying	0.41
Industrial, Non-noxious	0.49
Industrial, Noxious	0.02
Institutional	**14.48**
Elementary and Secondary Schools, etc.	14.12
Colleges, Universities, etc.	0.11
Cultural Facilities	0.01
Hospitals and Nursing Homes	0.05
Religious	0.09
Public Administration	0.09
Parks and Recreational Open Space	**40.22**
Local Parks and Playgrounds	0.16
Private Recreational Facilities associated with Residential Developments	0.04
Beaches	0.03
Golf Courses, Public/Private	0.30
Metropolitan Parks	0.42
Everglades National Park	24.65
Water Conservation Areas	12.36
Nature Preserves and Protected Areas	2.21
Other	0.05
Transportation, Communication, and Utilities	**4.21**
Military Bases and Terminals	0.58
Railroads	0.15
Utilities and Communications	0.71
Streets and Roads	2.35
Expressways and Freeways	0.34
Dumps, Landfills, and Waste Plants	0.05
Other	0.03
Agriculture	**5.67**
Groves	1.33
Crops	2.92
Grazing, Animal Farming, and Feed Lots	0.57
Plant Nurseries	0.31
Other	0.03
Fallow	0.51
Undeveloped	**17.62**
Undeveloped, Privately Owned	8.35
Undeveloped, Government Owned	0.15
Environmentally Sensitive, Private	8.73
Environmentally Sensitive, Government Owned	0.39
Inland water	**1.11**
Coastal water	**9.90**

constitute over 90% of the county's land area. About 80% of the remainder is undeveloped as a result of strict land use restrictions. Only 1.2% of the acreage in Monroe County is currently developed. Land use in Dade County is dominated by parks, recreational areas, and institutional uses. Together these classifications make up about 55% of the area of the county. An additional 29% of Dade County is composed of coastal and inland waters and undeveloped land.

WATER RESOURCES

Issues of water supply and allocation have been critical in the South Florida area for many years. The Florida Keys have no potable water. Collier County lacks the infrastructure (well fields and water supply lines) necessary to deliver water to a rapidly growing population. In Dade County, the destruction of wetlands has disrupted the aquifer recharge process and caused saltwater intrusion into the underground water supply.

The water for the South Florida area comes chiefly from underground sources or aquifers. An aquifer is a thick layer of porous rock through which water passes and is stored. Water for the South Florida area is drawn mainly from the Lower Tamiami and Biscayne Aquifers. These aquifers are recharged by local rainfall, by streams coming from the north, and by hillside runoff. Adequate rainfall is essential for maintenance of water supplies. For this reason, water supply problems in the South Florida region tend to be seasonal. Water is typically abundant during the summer months when rainfall is plentiful, and more scarce during the winter months when rainfall is less. The winter months are a peak water consumption period due to the influx of tourists.

The problem of saltwater intrusion into aquifers is one of great concern to the South Florida area. When water is withdrawn from an aquifer at a rate faster than the aquifer can be recharged, a void is created. In coastal areas, this void is often filled by seawater which seeps into the aquifer. When this happens, the water is degraded and may be rendered unsuitable for drinking.

Collier County

Water is provided by a number of public and private sector water systems in Collier County. The public sector systems include the City of Naples, Everglades City, and Collier County. There are three independent water supply districts and eight private companies that provide water under certification from the Florida Public Service Commission (Collier County Utilities Division 1989):

- Imokalee Water and Sewer District
- Pelican Bay Improvement District
- Port of Islands Community Improvements District
- Copeland Water and Sewer Company
- Florida Cities Water Company
- Marco Islands Utilities Inc.
- Marco Shores Utilities Inc.
- North Naples Utilities, Inc.
- Orange Tree Utility Company
- Vineyards Utility, Inc.
- Wyndemere Services, Inc.

Collier County water management officials say that the ability to construct the necessary infrastructure (well fields and water supply lines) to provide potable water to newly developed areas is an important constraint on the development of the county.

Growth is so rapid in Collier County that the ability to keep up with water demand is a continuing problem. The constraint arises not from the lack of available water resources, but from the lack of primary pumping, treatment and distribution facilities (R. Wiley, pers. comm. 1989, Collier County Water Management Department).

New supplies of water used in Collier County are drawn from well fields in the eastern portion of the county. The source of this water is the Lower Tamiami Aquifer, which is dependent on recharge that takes place mainly in Lee and Hendry Counties. There is a plentiful source of water in the deeper Floridan Aquifer, but this water is highly mineralized and not suitable for drinking or other household uses.

Water use restrictions have been imposed in recent years in the coastal communities of Collier County (Marco Island and Naples). These restrictions were lifted only after heavy summer rainfall replenished the aquifer and reduced the threat of saltwater intrusion.

To provide any significant new water supply to outer continental shelf (OCS) oil and gas operations, Collier County would be required to construct new water supply facilities and well fields. Although there is a constraint on available potable water, a large supply of non-potable water could be provided.

Dade County

Jurisdiction for water facilities in Dade County falls under the Miami-Dade Water and Sewer Authority Department. The source of the Dade County water supply is the Biscayne Aquifer, which is mainly recharged by local rainfall (Metro Dade County Planning Department [MDCPD] 1988b). As with the rest of South Florida, the most difficult water supply problem facing Dade County is not the overall quantity of water available but the seasonal variation in rainfall that provides the water supply.

Recharge and storage are managed by the South Florida Water Management District. Saltwater intrusion is a major problem in Dade County. Stream flow and high water tables prevent seawater from moving inland during rainy periods, but in times of drought, intrusion is a constant problem.

When a water plant reaches 90% of its capacity, the Dade County Department of Environmental Resources Management designates it for close monitoring of available capacity. As of the autumn of 1987, three plants were so designated. Dade County facilities have approximately 31 million gallons per day (MGD) of remaining supply capacity out of a total rated capacity of 383.33 MGD. On an average day, Dade County uses 296.3 million gallons. The maximum daily demand is 353.61 million gallons (MDCPD 1988a).

Water demand is projected to grow to 447.8 MGD in 2010 on an average day and to 537.3 MGD on peak days. Plant capacity is expected to become increasingly tight around the turn of the century. Total plant capacity is expected to grow to only 525 MGD by 2010 (MDCPD 1988a).

The capacity constraints facing Dade County make it unlikely that water could be made available for OCS oil and gas development without major new investments in water facilities. More importantly, all of South Florida is currently experiencing a major drought that has required water use restrictions in several counties, including those in the study area. The drought has further limited the flow of rivers and streams feeding Everglades National Park, seriously threatening the ecology of the park.

Monroe County and the Florida Keys

Although the Florida Keys are surrounded by water, their only local source of potable water is the capture of rainwater in tanks, or the desalinization of seawater. Capture of rainwater will not provide sufficient supplies at current use levels, and desalinization is prohibitively expensive. As a result, the Keys are supplied with water through a pipeline from the mainland. The Florida Keys Comprehensive Plan projects that this pipeline will be adequate to serve existing and projected needs through the year 2005 if additional capital expenditures are made (Monroe County Board of County Commissioners [MCBCC] 1986).

The Florida Keys Aqueduct Authority (FKAA) is charged with the task of developing and maintaining potable water facilities in Monroe County. The FKAA was created by the Florida Legislature in 1937 as the Florida Keys Aqueduct Commission (FKAC). In 1949 the FKAC, in cooperation with the U.S. Navy, constructed a 46-cm diameter pipeline from the mainland along the entire length of the Keys. In 1981, substantial improvements were made in the system, again with the cooperation of the Navy. The pipeline diameter is now 91 cm from Florida City to Key Largo, 76 cm from Key Largo to Marathon, and 61 cm to Stock Island. Some stretches of the original 46-cm pipeline are also still in use (MCBCC 1986).

The primary source of water for the Keys is the Florida City well field in Dade County. This water is drawn from the Biscayne Aquifer, treated at the Florida City water treatment plant, and sent to the Keys via the pipeline. The FKAA also has storage facilities along the pipeline with a total storage capacity of 30 million gallons (MCBCC 1986).

In addition to the water pipeline, the FKAA also maintains a reverse osmosis desalinization plant in standby condition on Stock Island. This plant is maintained to provide for system emergencies, shutdowns, or peak consumption periods. The plant has a capacity of 2.7 MGD and can be brought on-line in four hours (MCBCC 1986).

The FKAA has about 675 km (364 nmi) of distribution pipelines. It is anticipated that a large fraction of this system will be in need of replacement in the near future. A program to upgrade the system began in 1982, financed by a surcharge based on a 10-year schedule (MCBCC 1986).

The upgrade program is also designed to provide adequate water flow for fire protection. Until recently, pressure in the water distribution system has been inadequate for this purpose due to insufficient storage and pumping facilities (MCBCC 1986).

Because water supplies to Monroe County are obtained from outside sources in Dade County, and because of the serious constraints already facing the water distribution system in Dade County, it can be concluded that no major new OCS operation could expect to be supplied from a location in the Florida Keys.

MARINE TRANSPORTATION AND PORTS

The three-county area is served by four major ports (South Florida Regional Planning Council [SFRPC] 1984a,b):

- The Port of Palm Beach, which is defined as Lake Worth extending from the Riviera Bridge to the Southern Boulevard Bridge.

- **Port Everglades**, which includes the section of the Intracoastal Waterway from the Las Olas Boulevard Bridge to Washington Street, the Dania Cut-off Canal, and the New River.

- **Miami Harbor**, which includes all of the Miami River extending along Biscayne Bay to include Baker's Haulover Cut and Fisherman's Channel, as well as the Government Cut area.

- **Key West Harbor**, which covers all port facilities in the Florida Keys area.

There are no ports in Collier County. Although Port Everglades and the Port of Palm Beach are located outside of the three-county area, both of these ports are important to the study area. Most of the petroleum products used in the South Florida area enter through Port Everglades and the Port of Palm Beach.

Table 11.9 shows the shipping weight and value of imports and exports through South Florida ports in 1986.

The Port of Miami is the leading location for passenger ship arrivals and departures in Florida, whereas Port Everglades dominates the liquid petroleum market (SFRPC 1977). Very little commercial shipping passes through Key West.

Several factors influence the economic significance of a port. Water depth is probably the most important. Deep ports can accommodate larger, heavier vessels. The Port of Miami currently has a depth of 11.6 m; Port Everglades, 11.4 m; the Port of Palm Beach, 10.1 m; and the Port of Key West, 8.6 m (pers. comm. with port administrators, March 1990).

Table 11.9. Shipments through South Florida ports in 1986 (From: Bureau of Economic and Business Research 1988).

Port	Exports		Imports	
	Weight*	Value†	Weight*	Value†
Port Everglades	658	444	7,158	1,387
Key West	1	1	5	1
Miami	2,081	3,019	3,385	2,408
Palm Beach	1,734	1,136	1,518	349
Total	4,474	4,600	12,066	4,145

* Weight in millions of pounds.

† Value in millions of 1986 dollars.

The distance of a port from shipping lanes is also important. Port Everglades and the Port of Palm Beach are within 3 km (1.6 nmi) of the Atlantic shipping lanes. The Port of Miami and the Port of Key West are both roughly 8 km (4.3 nmi) from the major shipping lanes (SFRPC 1977).

The distribution area served by a port is a major factor influencing the volume of cargo handled. Miami and Port Everglades have the most port-related economic activity and the largest distribution areas.

The economic impact of a port is measured as the income generated by port and port-related activities. The economic impact of a port stems from the handling, transferring and processing of cargo. Ports that handle cargos that receive less handling have smaller economic impacts. The Port of Miami, which has a relatively large passenger traffic, has a larger economic impact than Port Everglades, which handles a relatively large quantity of refined petroleum products. In 1975, the total direct and indirect economic impact of ports in the South Florida area were (in 1987 dollars) $487 million for the Port of Miami, $257 million for Port Everglades, and $67 million for the Port of Palm Beach (SFRPC 1977).

The Port of Miami has 3,660 m of berthing and can handle up to 26 vessels at one time. It is located on Dodge Island in Biscayne Bay. Responsibility for the management of the port rests with the Seaport Department of Metropolitan Dade County (Howard Publications, Inc. 1977). Dodge Island is classified as a "conservation area." A seagrass bed "preservation area" is located immediately south of Dodge Island. Dredge and fill activities related to port operations threaten the Biscayne Bay Aquatic Preserve. These activities increase the amount of siltation which threatens marine vegetation. Because of the environmental sensitivity of the port area, the Dade County Seaport Department has agreed with the City of Miami to limit the operations of the port to high-value cargo and passenger services (SFRPC 1977). This means that bulk cargos such as petroleum are not handled.

Port Everglades is the largest seaport in the South Florida area. Located at the city limits of Fort Lauderdale and Hollywood, Port Everglades occupies 744.6 ha. It has 27 berths for ocean going vessels (Howard Publications, Inc. 1977). The depth of Port Everglades, together with its large turning basin makes it ideal harbor for large vessels, particularly oil tankers. Nineteen major oil and gas companies use Port Everglades as their supply point for South Florida. In 1979, over 6.5 million tons of refined petroleum products entered through Port Everglades. This represents almost half of the total tonnage for the port. This also represents 88% of the petroleum tonnage entering through South Florida ports (SFRPC 1984b).

The Port of Palm Beach is located on a 24.3-ha parcel of land adjacent to Lake Worth. The port has 17 berths totalling 1,200 m of dock space.

Most of the cargos entering the Port of Palm Beach are general in nature. Petroleum products accounted for about 30% of all tonnage in 1979, making them the single most important cargo. Passenger traffic through the Port of Palm Beach has been declining since 1971 (SFRPC 1984b).

Since 1977, the Port of Key West has grown from a simple facility that was used only for emergencies and fuel stops to a modern port. By 1979 the port was handling a quarter million tons of cargo and 23 thousand passengers (SFRPC 1984b). This, in combination with the recommissioning of the Key West Harbor Naval Base, has made Key West an important port area in the eastern Gulf of Mexico. The location of Key West Harbor would ordinarily make it an ideal location for basing OCS oil and gas

activity. Water supply constraints and the traditional use of Key West Harbor as a location for recreational and military uses make it unlikely that this will occur.

Exploratory drilling activity on the Southwest Florida continental shelf north of the study area has been supported in recent years from Port Manatee at the southern shore of Tampa Bay (Minerals Management Service [MMS] 1989b, p. 112). However, oil industry spokesmen indicate that a permanent supply base for leases in the South Florida OCS area would most likely be located outside of Florida, because of the specialized facilities and labor force already in place in the northern Gulf of Mexico.

Vessel Traffic

The large volume of petroleum products moving through the Straits of Florida makes an analysis of marine traffic and potential hazards important. Hazard areas are defined as crossing or merging areas within a 15- to 30-day drift range of the South Florida region. Drift range is important because crude oil and refined products spilled in water have been shown to weather and break down within 30 days (SFRPC 1984b). Four hazard areas have been identified within the Straits of Florida and South Atlantic area.

The first hazard area is 21 km (11.3 nmi) south-southeast of West Palm Beach. The crossing of north-south traffic by westbound traffic and the heavy traffic entering and leaving the Port of Palm Beach led the Coast Guard to identify this area as hazardous in 1976 and 1980 studies (SFRPC 1984b).

The second hazard area is located 19.3 km (10.4 nmi) southeast of Fort Lauderdale. In this area, the petroleum and other cargo originating in and destined for Port Everglades intersects with northbound and southbound traffic. The large quantities of petroleum products moving through Port Everglades make this area particularly hazardous (SFRPC 1984b).

The third hazard area, 21 km (11.3 nmi) southeast of Miami, is the area where Miami Harbor traffic merges into the shipping lanes. In addition there is a large amount of recreational boat traffic in this area (SFRPC 1984b).

The final hazard area is approximately 22.5 km (12 nmi) south of the Dry Tortugas. This area is hazardous because of the convergence of vessels traveling through the Straits of Florida. An oil spill in this area would likely be carried through the Straits by the Florida Current and deposited on the South Florida coastline (SFRPC 1984b; see also **Chapter 12** for discussion of oil spill trajectories).

Marinas

Marinas accommodate the demand for recreational boating facilities and services. They are defined as docks or basins that provide secure moorings for motorboats and yachts and often offer supply, repair, storage, and launching facilities (SFRPC 1984a). In addition, most marina facilities sell gasoline and fishing gear.

The South Florida region has a large number of marina facilities. In Collier County alone, 106 marinas were counted in 1984 (SFRPC 1984a). In 1986, the South Florida Planning Region, which includes Broward, Dade, and Monroe Counties, had 510 saltwater marinas (Florida Department of Natural Resources [FDNR] 1987b; Pompe 1990). Many of these marinas were built as condominium mooring facilities, however, and are not open to public use.

The 1988 Florida Cruising Directory shows that Collier County has only eight commercial marinas located in the Marco Island and Naples vicinity. Monroe County has almost 50 marinas along the Keys, with a large number in Key West. Dade County has over 60 marinas along the Atlantic coast and in Biscayne Bay (Waterways Cruising Club, Inc. 1988).

Table 11.10 compares pleasure boat registrations to the number of wet and dry storage areas in 1980 to 1981. Environmental constraints make it unlikely that the number of marina facilities can be expanded to meet a burgeoning demand for recreational boating facilities.

In 1980, the marina and boatyard industry in Florida had estimated sales in excess of $150 million (1987 dollars) and provided direct employment of 3,100 persons plus $97.9 million in value added. Because of the labor intensiveness of the industry, indirect economic impacts are quite large. The total (direct and indirect) economic activity generated by the marina and boatyard industry in Florida was estimated to exceed $327 million (1987 dollars) (Milon et al. 1983a).

MILITARY USES

The majority of the study area lies within military warning areas and test areas. These are multiple use areas in which military operations and other activities, such as oil and gas production and commercial fishing, take place together. The greater part of the study area lies within military warning areas W-174 and W-465. Within these regions, Department of Defense agencies practice air gunnery, air combat maneuvers, high altitude fighter radar intercepts, aerobatic flight training, and instrument flight training. The military warning area designation does not give the military a first use or priority use right to these areas, but does allow the Federal Aviation Administration to direct air traffic over or around these regions (MMS 1986).

Possible conflicts between military operations and OCS oil and gas activities include collisions of military craft with stationary and moving oil and gas vessels; air space conflicts between military and oil and gas aircraft; the release of electromagnetic signals by oil and gas operations; and the presence of spent ordnance on the seafloor in some OCS areas.

Table 11.10. Comparison of boat registrations to the availability of wet slips and dry storage in public and private marinas, 1980 to 1981 (From: Milon et al. 1983b).

Area	Registered Pleasure Boats	Dry Storage	Wet Slips
Collier County	9,200	574	792
Dade County	38,223	1,668	2,480
Monroe County	9,176	1,979	1,746
Three-County Area	56,599	4,221	5,018
State of Florida	480,864	20,999	24,141

Space-use conflicts in these areas will arise with increased military training and testing operations and with increases in oil and gas exploration and development activities. In the past, the U.S. Department of the Interior (USDOI) has included a set of stipulations in the OCS lease contracts designed to minimize these potential conflicts (MMS 1987). These stipulations would have only minor effects on oil and gas operations in the study area. The effectiveness of these stipulations is reflected in the absence of even a single accident involving military and oil and gas activities in these areas through 1986 (MMS 1987).

The desire by the Department of Defense to maintain a strong presence in the Caribbean and the ideal climate for pilot training in the lower Florida Keys are expected to lead to a doubling of Naval personnel in the Keys to over 6,000 persons through the year 2005 (MCBCC 1986). Increased aircraft activities associated with the Boca Chica Naval Air Station will increase possible use conflicts with offshore oil and gas activities. Airspace conflicts will be most acute for oil and gas activities based in the Lower Keys or for offshore activities near this location.

COMMERCIAL AND RECREATIONAL FISHING

Commercial and recreational fishing are major South Florida industries, with each making a substantial contribution to the local and State economies. Commercial exploitation of the Gulf waters off South Florida dates to the 1700s, when Spanish fleets used this productive region to supply fish to Spanish colonies in Cuba and the West Indies (Cato 1985). Development of a recreational fishing industry had to await the construction of a transportation network allowing anglers into the region. By the early 1900s, this transportation network was in place and the Florida Keys were gaining a reputation as an outstanding sport fishing region (MCBCC 1986). Since that time, the recreational fishing industry in the study area has continued to grow in size and importance to the local economy. (See **Chapter 7** for information on fisheries biology).

Commercial Fishing

Data for 1987 commercial fishing industry landings in the three-county area are presented in **Table 11.11**. Unlike fishing industries in many other states with important commercial fisheries, the fishing industry in Florida relies upon a wide variety of species for its total harvest. The pink shrimp harvest is Florida's most important contributor to both landings and value, but represents just 20% of total landings (National Marine Fisheries Service [NMFS] 1987). Other large seafood producing states, such as Louisiana, Texas, Massachusetts, and Alaska rely more heavily on one major species for total production than does Florida.

Of the species harvested in the study area and listed in **Table 11.11**, pink shrimp and spiny lobster account for over 40% of landed weight and just under 50% of ex-vessel value. The study area supplies approximately 20% of State shrimp production and 93% of State spiny lobster production (NMFS 1988). Production of spiny lobster in the study area represents over 77% of total U.S. production of this species (NMFS 1987). Shellfish, because of their high value to weight ratio, are the economically most important component of the South Florida fisheries. Grouper, snapper, mackerel, and mullet are the most important finfish species in the South Florida fisheries. Overall, finfish contribute over 40% of total landings by weight but account for just 20% of total ex-vessel value (**Table 11.11**).

Of the three counties in the study area, Monroe County is responsible for the majority of the landings and ex-vessel value. Most of the Monroe County catch is landed at Key West. The traditionally high value of the landings at Key West made that port the 18th most important fishing port in the Nation in 1986 (NMFS 1987). Collier County supplies about one-fifth of total landings in the study area. Dade County provides <9%. Statistics for the three counties are provided in **Table 11.12.**

Table 11.11. Commercial fishery landings and ex-vessel value for the three-county area in 1987 (From: National Marine Fisheries Service 1988).

Fishery	Landings (thousands of pounds)	Value (thousands of 1987 dollars)
Finfish Variety		
Grouper, Red	1,930	2,683
Snapper, Yellowtail	1,267	2,293
Snapper, Mangrove	569	819
Snapper, Mutton	292	741
Pompano	212	633
Mackerel, Spanish	1,931	656
Mackerel, King	569	620
Mullet, Black	1,612	613
Grouper, Black	303	536
Dolphin	291	320
Shark	382	198
Amberjack	419	180
Swordfish	55	184
Ballyhoo	455	146
Misc. Food Fish	363	120
Others	2,051	1,228
Total Finfish	12,701	11,970
Shellfish Variety		
Lobster, Spiny	5,876	13,926
Crabs, Stone, Large	1,714	9,068
Crabs, Stone, Medium	679	2,988
Crabs, Stone, Ungraded	495	2,565
Crabs, Stone, Small	256	1,154
Shrimp, Pink	6,604	15,520
Shrimp, Rock	75	25
Shrimp, Brown	10	19
Shrimp, Bait	384	4,958
Other Shrimp	27	7
Other Shellfish	220	231
Total Shellfish	16,340	50,464
TOTAL FISHERIES	29,041	62,434

Table 11.12. Distribution of total catch and value by county in 1987 (From: National Marine Fisheries Service 1988).

County	Total Catch (thousands of pounds)	Value (thousands of 1987 dollars)
Collier	5,680	11,419
Dade	1,543	5,428
Monroe	21,818	45,587
Total	29,041	63,434

Although the commercial fishing industry is certainly an important component of the South Florida economy, it is not a growth industry. **Figure 11.3** provides information on seafood landings for the three counties over the last 11 years. The highest landed weight for this period was achieved in 1981 (39.0 million pounds) and the lowest landed weight two years later (25.2 million pounds). The average annual landings over this period was just under 31 million pounds, with little evidence of a trend either upward or downward. Growth of the commercial fisheries is constrained by the size of fish stocks. Increased fishing effort might increase total landings over a short time period, but because fish stocks are assumed to be exploited at or beyond their optimal levels at present, no sustained increase in landings can occur.

Concern over the possibility of overfishing led to the creation of the Marine Fisheries Commission (MFC) within the FDNR in 1983. The MFC is responsible for regulations controlling all marine life (except endangered species) within Florida jurisdictional waters. The Commission's major responsibility is the conservation and management of the State's marine resources for the continued health and abundance of those resources. Within this broad framework, the MFC regulates fishing activities in order to "permit reasonable means and quantities of annual harvest, consistent with maximum practical sustainable stock abundance on a continuing basis" (Christie 1989).

As of September 1988, rules have been set for the management of seven fisheries important to the South Florida economy:

- Spiny lobster
- Snapper and grouper
- Queen conch
- King and Spanish mackerel
- Billfish
- Stone crab
- Shrimp

These fisheries are thought to be operating at or beyond optimal sustained yield. Nearly all of the important commercial species that are harvested in the study area are included on the list of regulated species. The best hope for growth in the South Florida fisheries lies not with increased exploitation of these species but with the harvesting and marketing of nontraditional seafood resources (Cato 1985). Increased harvests of currently under-utilized species, such as deep-sea crustaceans, and pelagic and ground fish, could lead to renewed growth in the fishing industry. These non-traditional marine resources represent a potential addition of 2.5 billion pounds to total Florida landings annually (Cato 1985). If the South Florida region were to bring its rate of participation in these fisheries to the same level as the more traditional fisheries (about 20% of State landings), landings in the study area could rise by 500 million pounds annually, or more than 15 times current landings.

A 1984 Sea Grant project by Otwell et al. (1984) investigated the potential for development of the Gulf deep-sea crab fishery. Their results indicated a potentially large fishery that could be harvested with existing equipment. Some marketing efforts would be required, but the new resource could potentially augment or supplant the existing red crab market.

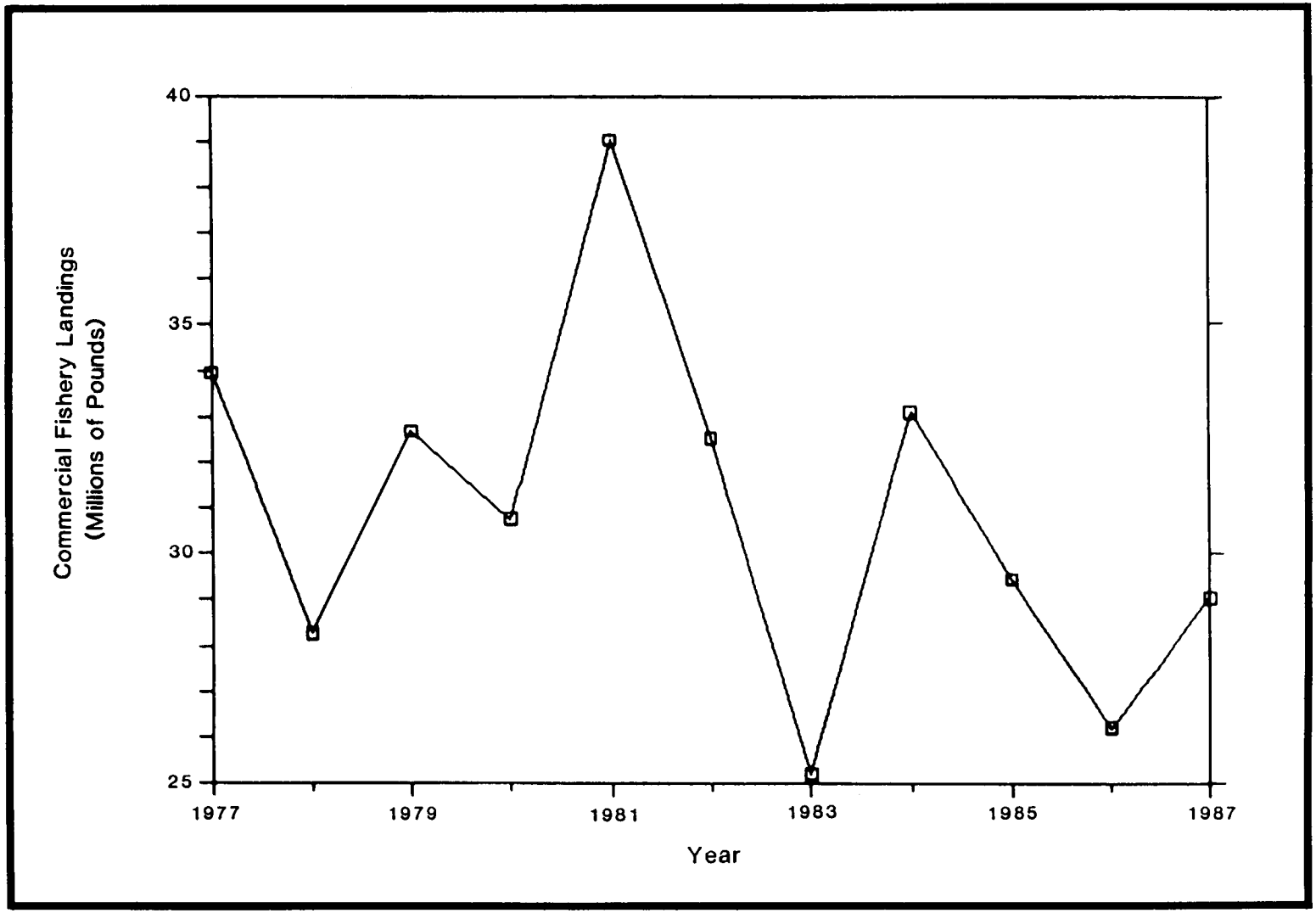

Figure 11.3. Commercial fishery landings for the three-county area, 1977 to 1987 (From: National Marine Fisheries Service 1988). The 1977 to 1985 figures are adjusted for reporting inconsistencies.

The ex-vessel value of commercial fishery landings in the study area provides a method for comparing the size of the fishing industry in different areas. However, ex-vessel value does not adequately measure the overall effect the commercial fisheries have on the local economy. Three alternative measures are often used as indicators of overall economic effects: output, income, and employment (Rockland 1988). Output is the value of the product produced by the industry. Income is the amount of earnings received in conjunction with the output. Employment refers to person-years of employment generated by the output (one person-year is equal to one person working 40 hours per week, for 52 weeks). A study of commercial and recreational fishing in the Florida Keys estimated that the commercial fishing industry in Monroe County generated output (1986 values in 1987 dollars) of $41 million, income of $14.8 million, and employment equal to 1190.5 person-years (Rockland 1988).

These estimates include output generated from the harvesting, wholesaling, retailing, and restaurant preparation of commercial seafood, but do not include a multiplier to account for induced output, income, and employment. Including both direct and indirect economic effects, Rockland (1988) estimated that the Florida Keys fisheries provided over $160 million in output for the Florida economy in 1986.

Similar estimates of output, income, and employment are not available for Collier and Dade Counties. However, fisheries harvests for Collier and Dade Counties generate approximately 37% as much ex-vessel value as Monroe County. Multiplying the Monroe County estimates by 1.37 gives a rough estimate of the overall impact of the three-county area fisheries on the study area economy as well as on the State economy (see **Table 11.13**).

Recreational Fishing

Much of the value of the marine resources of the South Florida region is embodied in their application to recreational activities. This is particularly true of the region's fishery resources. The output or product of a recreational fishery is much greater than the market value of the fish that are caught. Unlike commercial fisheries where fish are caught for market sale, it is the fishing experience that gives recreational fishing its greatest value (Bell et al. 1982).

Table 11.13. Commercial fisheries output, income, and employment estimates (Adapted from: Rockland 1988).

	Output (thousands of 1987 dollars)	Income (thousands of 1987 dollars)	Employment (person-years)
Monroe County Fisheries			
Impact in Monroe County	$41,071	$14,828	1,190.5
Total Impact in Florida	$160,518	$51,682	4,932.5
Three-County Area Fisheries*			
Impact in Three-County Area	$56,267	$20,314	1,631.0
Total Impact in Florida	$219,909	$70,804	6,757.5

* Three-county estimates were constructed by multiplying the Monroe County estimates by a factor of 1.37. Dade and Collier Counties together account for 37% of the ex-vessel value of Monroe County fisheries.

Recent studies of the South Florida recreational fisheries have focused on valuing these fisheries by measuring the total expenditures of the anglers engaging in the fishing activity. Rockland (1988) used survey data from fishermen as well as local businesses to estimate expenditures and participation rates for charterboat, guideboat, private boat, headboat, and pier and bridge fishing for Monroe County. Generating economic impact estimates from these data also involves measuring the numbers of vessels and trips taken and the operating margins for these operations. Rockland (1988) estimated that the recreational fishing industry resulted in output for Monroe County in excess of $63 million. This is 50% higher than the output estimate for the commercial fishery. Extrapolating this estimate to project the economic effects of the Monroe County recreational fishing industry on the entire State results in an output estimate of over $244 million (**Table 11.14**).

In an earlier study of saltwater recreational fisheries, Bell et al. (1982) estimated that slightly over 5 million anglers engaged in recreational fishing in the State of Florida during the 1980 to 1981 season for a total of over 58 million days fished. On the basis of estimated expenditures by residents and tourists for recreational fishing, the authors concluded that the recreational fishing industry was responsible for approximately $5.05 billion in direct and indirect expenditures throughout the State of Florida in the 1980 to 1981 study period. These expenditures were estimated to support 123,878 jobs paying $1.37 billion in wages and salaries (Bell et al. 1982).

The above study included participation and expenditures by tourists as well as Florida residents. Participation rates in recreational fishing for each group (tourists and residents) were estimated to be 9.67% and 29.8%, respectively. Assuming these rates have remained relatively constant through 1987, and based upon a 1987 study area population of 2 million and an annual tourist visitation level of 6 million, we estimate that 1.18 million persons engaged in recreational fishing in the study area in 1987.

Table 11.14. Recreational fisheries output, income, and employment estimates (Adapted from: Rockland 1988).

	Output (thousands of 1987 dollars)	Income (thousands of 1987 dollars)	Employment (person-years)
Impact of Monroe County Fisheries in Monroe County	$63,599	$21,260	1,605.1
Total Impact of Monroe County Fisheries in Florida	$244,483	$77,007	6,037.9

Assuming that expenditure and multiplier parameters have remained unchanged over this period, and correcting for changes in the general price level, it can be estimated that recreational fishing by residents and anglers in the three-county area generated $1.18 billion in total direct and indirect economic activity for the State of Florida in 1987. This represents about 0.5% of Gross State Product in 1987. Just over 25,000 employees would be supported by this level of activity. These data are summarized in **Table 11.15.**

Using the same technique as above, the total direct and indirect impact of all recreational fishing on the Florida economy is estimated to be $6.9 billion for 1987, or about 4% of Gross State Product.

As noted earlier, the major output of recreational fishing is not the fish, but rather the fishing experience. The above estimates of the economic impact of recreational fishing do not value the activity itself but only expenditures (and secondary impacts) associated with acquiring the fishing experience. The fishing experience itself is what economists call a "nonmarket activity" (Bell et al. 1982). Estimating the value of nonmarket activities is very difficult because the product is not directly marketed and thus no market price is established. One technique often used to estimate the value of nonmarket goods is termed contingent valuation. Contingent valuation relies upon the use of surveys to ascertain the willingness of individuals to pay for the nonmarketed good (Tietenberg 1988). Bell et al. (1982) used contingent valuation techniques to estimate the satisfaction received (user value) from the use of the saltwater recreational fisheries. The total estimated user value of the recreational fisheries in 1980 to 1981 was $2.07 billion. Assuming that the quality of the recreational fishing experience has remained constant since the original study, and adjusting this figure for the price level changes through 1987 and for the growth of population and tourist visits, we estimate total 1987 user value to be $590 million for the study area and $3.5 billion for the State.

Table 11.15. Recreational fisheries total economic impact and employment estimates for the three-county area (Adapted from: Bell et al. 1982).

	Tourist	Resident	Total
Thousands of Participants in 1987	580.2	597.0	1,177.2
Average Annual Economic Impact Per Angler*	$1,447.37	$568.89	N/A
Total Economic Impact†	$839.76	$339.63	$1,179.39
Employment Induced	19,708	5,585	25,293

* 1987 dollars
† millions of 1987 dollars

Finally, we can estimate the present discounted value of the recreational fisheries by recognizing that user value is an annual flow and if it is expected to occur for a large number of years the present discounted value of the resource can be found as V = R/i, where

V = present value of the resource
R = annual return from the resource (total annual user value)
i = the discount rate.

As determined above, 1987 total annual user value is $590 million for the study area and $3.5 billion for the State. Using a discount rate of 0.10, the present discounted value of the study area recreational saltwater fishery is $5.9 billion, and $35 billion for the recreational saltwater fisheries of the State as a whole.

RECREATION AND TOURISM

Florida has become a mecca for outdoor recreation enthusiasts from the U.S. and an increasingly popular vacation spot for European, Canadian, and other foreign visitors. The rapid growth of tourism over the past decade attests to the desirability of Florida as a destination site for outdoor recreation. Unfortunately, the rise in population and tourism in Florida has increased the pressure on available outdoor recreation sites by making it more costly and difficult to acquire public lands for these purposes.

Outdoor recreation activities are generally subdivided into "user-oriented" and "resource-based" categories (FDNR 1987a). User-oriented recreational activities are those that can be provided almost anywhere for the convenience of the user. Examples include tennis, golf, baseball, and playground activities, as well as outdoor concerts, spectator sports, and botanical gardens. Resource-based recreation is dependent upon some element or combination of elements in the natural or cultural environment. Examples of resource-based recreation include hunting, fishing, boating, sightseeing, visiting historical monuments, and beach activities.

Information concerning outdoor recreation is obtained from *Outdoor Recreation in Florida* reports for 1987 and 1989 (FDNR 1987a, 1989). These reports are produced as part of a comprehensive plan to meet the recreational needs of the people of Florida. The reports provide estimates of the demand for various outdoor recreational activities based on survey data, including data adapted from the annual survey of departing Florida visitors conducted by the FDC. The standard unit for expressing recreational activities is the "user-occasion." A single user-occasion is said to occur each time an individual participates in a single outdoor recreational activity. User occasions are estimated for regional residents, Florida residents from outside each region, and for tourists. These estimates are then used to generate per capita participation rates for each group in each activity.

Participation rates for the top four outdoor recreation activities in Florida are presented in **Table 11.16.** The table indicates the importance of beach-related recreation and saltwater fishing to both residents and tourists.

It is not possible to determine the percentages of residents and tourists engaging in saltwater fishing activities from the FDNR report, but estimates from another study indicate that approximately 29.8% of Florida residents and about 9.67% of tourists engage in saltwater fishing (Bell et al. 1982).

Estimates of participation rates and user-occasions for tourists and residents engaging in each of the top rated outdoor recreation activities for the three-county area are presented in **Table 11.17.**

Table 11.16. Statewide demand for outdoor recreational activities: top four activities in 1985 (Adapted from: Florida Department of Natural Resources 1987).

	Saltwater Beach Activities	Swimming Pool Use	Bicycle Riding	Saltwater Fishing
Total User-Occasions (thousands)	131,932	147,905	69,731	29,155
Percent of Total User-Occasions	21.8	24.4	11.5	4.9
Resident User-Occasions	38,001	58,359	60,784	18,316
Participation Rate of Residents	2.69	4.38	5.06	0.59
Percent of Residents Participating	56.1	38.8	35.0	N/A
Tourist User-Occasions	93,931	89,546	8,947	10,839
Participation Rate of Tourists	2.85	2.62	0.26	0.32
Percent of Tourists Participating	57.8	48.0	5.6	N/A

Table 11.17. Study area demand for outdoor recreational activities: top four activities in 1987 (Adapted from: Florida Department of Natural Resources 1987).

	Saltwater Beach Activities	Swimming Pool Use	Bicycle Riding	Saltwater Fishing
Total User-Occasions (thousands)	20,952	21,519	13,683	5,341
Percent of Total User-Occasions	22.5	23.2	14.7	5.7
Resident User-Occasions	7,206	10,605	12,915	3,787
Participation Rate of Residents	3.59	5.29	6.45	1.89
Tourist User-Occasions	13,746	10,914	768	1,554
Participation Rate of Tourists	2.29	1.82	0.13	0.26

Over the past 13 years, the number of tourists visiting Florida annually has surged from 17.6 million in 1976 to almost 37 million in 1988 (Cato 1989; FDC 1989). The average annual growth rate of tourism over this period is approximately 8.5%, making tourism one of Florida's major growth industries. Visitors to Florida spent an estimated $24.34 billion dollars in 1987, ranking Florida second only to California in terms of total tourism expenditures (FDC 1989).

The major source of tourism data for Florida and for individual counties within Florida is derived from the annual visitor studies conducted by the Division of Tourism within the FDC. These studies are based upon surveys of non-Florida domestic residents departing the State through commercial airports or via State and interstate highways. Tourism information and tourist characteristics from survey participants are then used to estimate overall tourist characteristics and participation rates. Current information on foreign visitors to Florida is provided by the U.S. Department of Transportation and is based upon port of entry data. No other data sources are currently available for large area tourism in Florida.

Table 11.18 provides information on the origins and destinations of the majority of domestic Florida visitors. Just under 50% of all Florida visitors arrived by air in 1988. Of those that did, nearly 20% identified Monroe and Dade Counties as their primary destinations. This was the first year that the Orange-Osceola-Walt Disney World region surpassed Dade County as the State's number one tourist destination for air travel visitors. Between 1987 and 1988, Dade County's share of air travel visitors fell from 25.2% to 15.4%.

The data presented in **Table 11.18** indicate that nearly half of all air travel visitors come to the four South Florida counties of Monroe, Dade, Broward, and Palm Beach. Auto visitors tend to choose the northern counties as destinations, with Broward the only southern county in the top 10.

Findings for individual counties derived from the 1987 Florida visitor survey indicate that over 6 million tourists visited the three-county area in 1987. This suggests that roughly 18% of all tourist visits to Florida occur in the study area. A study by Curtis and Snows (1984) concluded that up to 19% of Gross State Product originates with tourism-related activities. Extrapolating this estimate to the study area, it appears that approximately 3.5% of Gross State Product (roughly $6.2 billion) was generated by study area tourism in 1986. This estimate includes both direct and indirect effects of tourist expenditures.

Table 11.19 provides information on the size of the Florida tourism industry and the value of direct tourist expenditures. **Table 11.20** presents information on employment and income generated by Florida tourism.

The data in **Table 11.20** indicate the importance of the tourism industry for the study area. Monroe County has a total labor force of 42,455 (1987). One in five Monroe County workers is employed in the tourism industry. For Collier County, roughly 15% of the work force is employed in tourism-related activity; for Dade County, the ratio is about 8% (Bureau of Economic and Business Research 1988).

Both air travelers and automobile travelers to Florida cite visits to friends and relatives and vacation travel as the number one and number two reasons for coming to the State (FDC 1989). Once they arrive, Florida visitors identify rest and relaxation as the number one intended activity, closely followed by beach use and visiting with friends and relatives. The top 10 activities listed by air and auto travelers are presented in **Table 11.21.**

Table 11.18. Top ten origins and destinations of domestic visitors to Florida in 1988 (From: Florida Department of Commerce 1989).

Air Visitors			Automobile Visitors		
Origin	Rank	Percent	Origin	Rank	Percent
New York	1	13.9	Georgia	1	14.4
New Jersey	2	7.2	Ohio	2	7.0
Ohio	3	6.1	New York	3	5.0
Pennsylvania	4	5.9	Tennessee	4	4.9
Massachusetts	5	5.4	Illinois	5	4.4
Illinois	6	5.2	Texas	6	4.4
Texas	7	4.4	Michigan	7	4.1
California	8	4.2	Pennsylvania	8	4.1
Michigan	9	4.0	North Carolina	9	4.0
Georgia	10	3.9	Alabama	10	4.0
Air Visitors			**Automobile Visitors**		
Destination	Rank	Percent	Destination	Rank	Percent
O-O-WDW*	1	21.6	O-O-WDW	1	21.8
Dade	2	15.4	Volusia	2	14.0
Broward	3	14.7	Bay	3	12.7
Palm Beach	4	10.5	Escambia	4	7.6
Pinellas	5	9.7	Pinellas	5	7.2
Hillsborough	6	9.0	Duval	6	6.8
Duval	7	5.4	Brevard	7	6.5
Lee	8	5.1	Hillsborough	8	5.9
Monroe	9	4.5	Broward	9	5.7
Sarasota	10	4.2	Okaloosa	10	5.3

* The Orange-Osceola-Walt Disney World area.

Table 11.19. Tourist visits and expenditures in 1987 (Adapted from: Florida Department of Commerce 1988f).

Area	Visitors	Tourist Expenditures (thousands of dollars)
Collier County	155,000*	79,828
Dade County	5,069,000	2,710,531
Monroe County	1,162,000	576,796
Three-County Area	6,386,000	3,367,153†
State of Florida	34,067,000	33,768,510

* Estimated by multiplying the Statewide visitor estimate by the share of tourism-related employment in Collier County.
† Estimated by multiplying the estimated visitor total by the average expenditure per visitor for the three-county area.

Table 11.20. Tourism-related employment and income in 1987 (From: Bureau of Economic and Business Research 1988).

Area	Tourism-Related Employment	Tourism-Related Payroll (thousands of dollars)
Collier County	9,206	8,885
Dade County	75,195	70,456
Monroe County	8,711	7,982
Three-County Area	93,112	87,323
State of Florida	564,291	448,195

Table 11.21. Top 10 activities for visitors to Florida in 1988 (From: Florida Department of Commerce 1989).

Air Visitors			Automobile Visitors		
Activity	Rank	Percent	Activity	Rank	Percent
Beaches	1	16.0	Rest/Relaxation	1	16.6
Rest/Relaxation	2	15.4	Visit Friends/Relatives	2	13.9
Visit Friends/Relatives	3	13.9	Beaches	3	13.4
Climate	4	13.4	Climate	4	12.7
Florida Attractions	5	8.4	Florida Attractions	5	10.5
Other	6	6.4	Fishing	6	6.1
Golf	7	4.6	Golf	7	4.7
Dancing/Night Life	8	4.1	Low-Cost Vacation	8	4.4
Boating	9	2.9	Other	9	3.4
Fishing	10	2.8	Water Sports	10	3.2

Foreign visitors to Florida represent a significant portion of total tourist visits. Nearly 2.5 million international travelers to the U.S. in 1988 listed Florida as their intended first destination. This represents about 22% of all international visitors to the U.S. and about 7% of all Florida tourists (FDC 1989). Of these tourists, nearly one half were European with the majority of the rest coming from South America, Central America, Mexico, and the Caribbean. In addition, nearly two million Canadians visited Florida in 1988. Unfortunately, visitation and expenditure rates are not available by county for international tourists; thus, more specific estimates of foreign tourism impacts within the study area are unavailable. The FDC *European Travel Study 1984* does provide some information on the demographic characteristics and activities most enjoyed by European visitors (FDC 1985a). The Florida Everglades are identified as one of the top four sightseeing attractions among European visitors. One in four European visitors identify the South Florida region as a primary destination.

Florida residents traveling to other parts of Florida constitute an important component of total tourism. A 1985 study of Florida resident travel behavior indicated that nearly 60% of Florida residents had taken at least one overnight travel trip within the State in the prior two years (FDC 1985b). For residents traveling in-State on trips of one week or longer, the Florida Keys tied with Orlando as the number one destination choice. For overnight trips of less than one week, the Keys came in second to Orlando. For all residents taking overnight trips within the State, beach- and water-related activities were the most important activity, followed by sightseeing (FDC 1985b).

For residents and nonresidents alike, beach and water-related activities rank among the top forms of enjoyment in the State. The FDNR estimates that over 50% of tourists and residents participate at least once a year in saltwater beach activities (FDNR 1987a). This suggests that over 25 million different people used Florida beaches at least once in 1988.

Florida's beaches have obviously great value to both tourists and residents, but because beach use is generally a nonmarket good, valuing that resource can be difficult. Relying on survey information to estimate the average expenditures of beach users, Curtis et al. (1980) were able to estimate total direct and indirect economic impacts from visitor use at Ft. De Soto Park in Pinellas County. Based on total economic impact, the authors estimated the annual income associated with each kilometer of beach in the park to be approximately $980 thousand (1987 dollars). Assuming that beach use will continue indefinitely, and at a discount rate of 10%, the present value of each kilometer of beach in Ft. De Soto Park would be $9.63 million (1987 dollars). This estimate relies only on the economic impact of the beach area and fails to take into consideration the value and satisfaction users received from the beach experience.

Bell and Leeworthy (1988) used a recreational demand model for tourists to estimate the extra market value of services obtained from Florida saltwater beaches. This technique differs from the traditional travel cost valuation approach in that tourists, because of the high initial cost of transportation, desire more, rather than fewer, beach days as travel cost rises. Estimates of the value of beach acreage derived from this study are based solely on tourist valuations and do not take into consideration the value of beaches to persons living close by. On the basis of this model, the authors estimated average consumer's surplus per beach day to equal $33.91. Using data from an earlier study (Bell and Leeworthy 1986) and a 10% discount rate, the authors estimated the value of Florida beaches to tourists to be $9.1 million (1987 dollars) per 0.4 ha.

Most of the study area coast is composed of saltwater marshes and mangrove swamps. However, there are numerous beaches in the study area including two State

recreation areas and some of the most pristine wilderness beaches in the State (Univ. of West Florida 1985).

Recreational boating and fishing are additional activities rated among the top 10 tourist activities. Recreational boating has also been a rapidly growing pastime with Florida residents. In 1987, over 614 thousand boats were registered in the State, about one boat for every eight Florida families (Cato 1989). Over 1,500 private and public marinas are available to serve this boating industry with the largest concentrations in South Florida. Approximately 1,300 charter fishing boats, party boats, dive operators, and other vessels are available for hire (Cato 1989).

Several studies have investigated the economic impact of recreational boating on the Florida economy (Milon et al. 1983a; Ellerbrock and Milon 1984; Milon and Adams 1987). These studies showed the recreational boating industry to be a major Florida industry, directly employing over 23,000 persons and creating $1.4 billion in economic output in 1985 (Milon and Adams 1987). However, these studies are not able to identify the specific impact of tourism-related recreational boating on Florida or the study area economies.

The recreational fishing industry is heavily influenced by the participation of tourists (**Table 11.16**). Bell et al. (1982) estimated that nearly 10% of Florida tourists and almost 30% of residents participate in saltwater recreational angling. These estimates and other parameters from the study suggest that the total economic impact associated with saltwater angling in 1987 in the study area alone, exceeded $1.1 billion.

It is important to note when considering the economic impacts of tourism, angling, and recreational boating that to a certain extent these impacts overlap. Tourists come to Florida for a variety of reasons, and some tourists will participate in both recreational fishing and boating during their stay. Because of these overlapping uses, it is not appropriate simply to add all these sectoral impacts together when estimating total economic impact.

MINERAL RESOURCES

The nearshore and continental shelf regions of the study area are thought to contain deposits of phosphate, calcium carbonate and quartz sands, and heavy minerals, as well as petroleum (Christie 1989). Those resources lying within Florida territorial waters are under the jurisdiction of the Board of Trustees of the Internal Improvement Trust Fund and the FDNR. Current policy promotes the exploration and development of onshore mineral resources that lie outside of environmentally sensitive areas. Little interest has been expressed in Florida coastal offshore mineral deposits other than petroleum, and no State leases for offshore mineral mining have been granted (Christie 1989).

Potentially economic deposits of phosphates and quartz sands are believed to occur on the continental shelf of the study area. However, the current world supply of phosphates from onshore sources has been more than sufficient to meet current demand, with the result that prices and industry activity have been slumping. Florida is one of the world's largest producers of phosphate. Current phosphate production is concentrated east of Tampa, where extensive pebble phosphate deposits are being surface mined. The State possesses large reserves of these and other types of phosphates (Fernald 1981). More costly offshore deposits are thus of little current interest. No prospecting or mining for OCS minerals has occurred on the West Florida shelf (MMS 1987).

Offshore mining of minerals other than petroleum products is a relatively recent occurrence and is tied directly to technological advances in the field. Although there currently are no offshore mineral exploration or mining activities in the study area, a potential for future activities does exist.

AREAS OF SPECIAL CONCERN

The South Florida area is fortunate in having some of the most pristine and productive coastal regions in the Nation. The hundreds of kilometers of shoreline are interspersed with keys and barrier islands and covered with mangrove forests, saltwater marshes, swamps, estuaries, and bays (FDNR 1988a).

The semi-tropical climate of South Florida, together with its location at the entrance to the Gulf of Mexico, combine to produce a set of environmental conditions not duplicated elsewhere in the U.S. Many of these areas have been deemed to be of such a special quality or unique character that they have qualified for National, State, or local conservation designations.

Some conservation designations are readily recognized--for example, State and National parks; others, such as aquatic marine preserves and archeological reserves, are less well known. The common thread among these designated areas is that they are all of special concern to the Nation and the world, as well as to local and State residents.

National conservation programs, coupled with the most aggressive State land acquisition program in the country, have worked to ensure that major portions of the South Florida region will be held in public trust. The South Florida study area contains over 60 sites that qualify as areas of special concern, with at least 10 additional sites now under consideration for conservation by the land acquisition programs of the State and Federal government as well as by private preservation groups such as The National Audubon Society and The Nature Conservancy.

Some areas of special concern within the study area, because of their geographic location or environmental sensitivity, will be more susceptible to possible adverse consequences of offshore oil and gas activities. These areas will be identified in the text with italicized numbers which correspond to those on the accompanying map **(Figure 11.4)**.

National Parks

Two National parks border the study area. Biscayne National Park (*6*), located in southeastern Dade County, encompasses 71,000 ha of mangrove shoreline, watery regions of Biscayne Bay, Atlantic waters and their associated coral reef formations, and the northernmost Florida Keys (Little 1987). The area was designated a National park in 1980 in order to preserve the "rare combination of terrestrial and undersea life, preserve a tropical setting, and provide an outstanding spot for recreation and relaxation" (Little 1987). The park is unusual in that 95% of its area is underwater. Biscayne National Park contains about 44 keys and islands in a north-south chain and access to the keys and islands is by boat only. The park is famous for its reefs, tropical fishes, bird life, shipwrecks, and unusual shoals and islands. Biscayne National Park had over 600,000 visitors in 1987, making it one of South Florida's major recreation sites (Bureau of Economic and Business Research 1988).

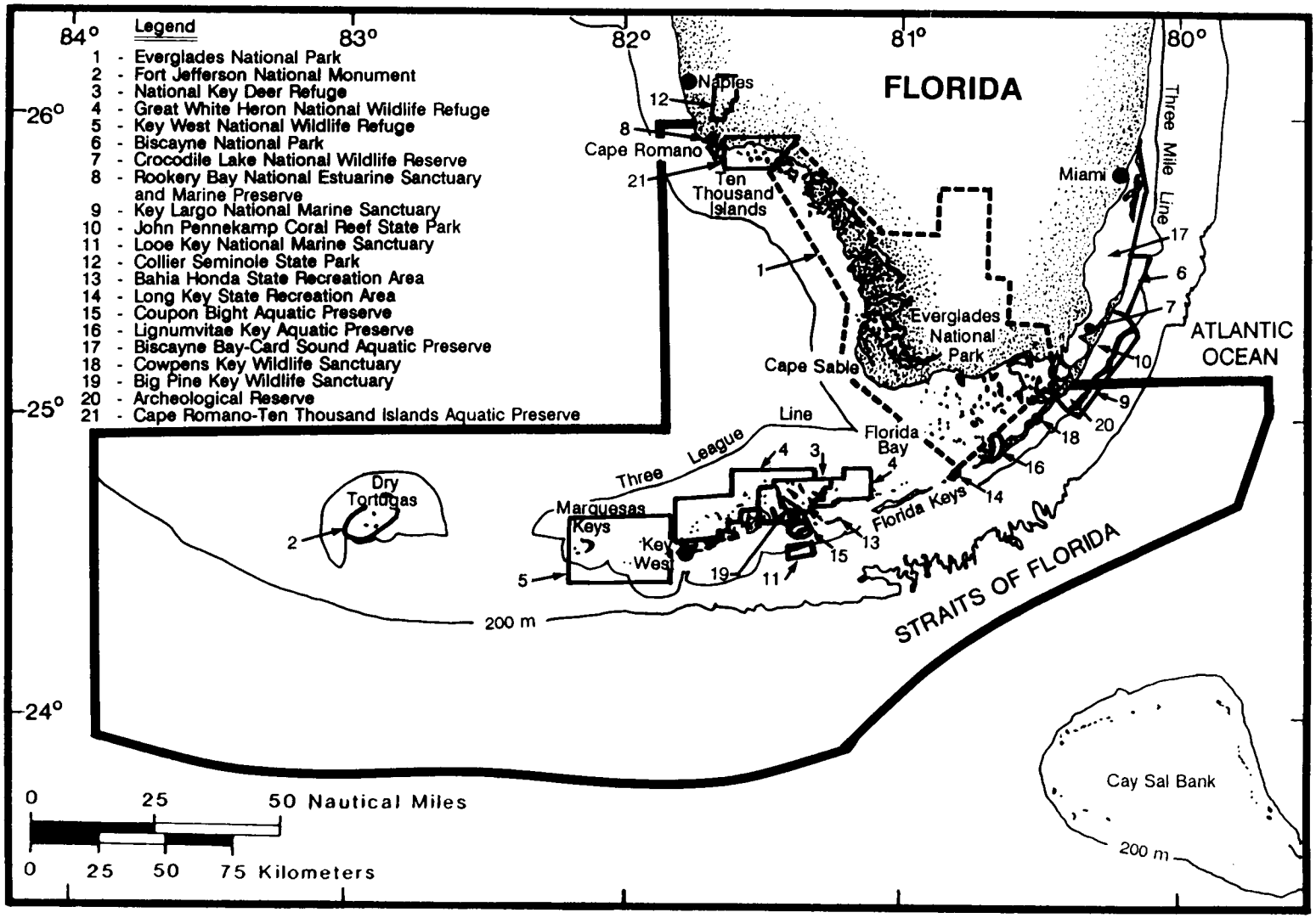

Figure 11.4. State and National parks, wildlife refuges, aquatic preserves, marine sanctuaries, and other areas of special concern within the study area.

Everglades National Park (*1*) encompasses 567,000 ha of marshy terrain at the tip of the Florida peninsula (Little 1987). The Everglades is the largest expanse of sawgrass in the world, and the 1947 creation of the park sought to preserve a pristine portion of that ecosystem (Morris 1987). While the park is best known for its abundance and variety of wildlife, particularly its bird life and alligators, the uniqueness of the ecosystem itself has resulted in the Everglades being designated as an International Biosphere Reserve and a World Heritage Site (United Nations Educational, Scientific, and Cultural Organization 1982; Little 1987).

Located within the park is a portion of the Ten Thousand Islands region where the average elevation is <1.5 m. The southern exposure of the Everglades on the Bay of Florida is characterized by numerous marshy hammocks and small keys. Many of these small keys contain stunning examples of pristine wilderness beaches. Indian, Rabbit, Turkey, and Lostmans Keys all sport outstanding examples of sandy tropical beaches, with most accessible only by water (Univ. of West Florida 1985).

Unlike most National parks, the legislation creating Everglades National Park provides that the area be permanently preserved as a wilderness area and that no development for the purpose of entertaining visitors be undertaken if that development interferes with preservation of the natural environment (SFRPC 1984b). This strong commitment to preservation has meant that most of the park remains relatively inaccessible and visitor facilities are small relative to the park's size. Nonetheless, almost 800,000 visitors made use of the park's facilities in 1987 (Bureau of Economic and Business Research 1988), and the park ranks as one of the top 10 attractions for visitors flying to Florida from other states (FDC 1988d).

National Monuments

Fort Jefferson National Monument (*2*) is the only National monument in the study area. The monument is located in the Dry Tortugas, about 110 km (60 nmi) west of Key West. Access is by water or sea plane (MMS 1986). The Dry Tortugas gain their name from the large number of turtles that nest here and the almost complete absence of drinking water. Fort Jefferson was built in the 1800s to provide a military vantage point for controlling vessel traffic into the Gulf of Mexico. However, the fort was never finished and never fired a shot in conflict. During and after the Civil War, the fort was used as a prison. Samuel Mudd, the physician who treated Abraham Lincoln's assassin, John Wilkes Booth, spent several years incarcerated here before being pardoned in 1869 (Univ. of West Florida 1985; Morris 1987). The relative inaccessibility of the Dry Tortugas restricts the number of South Florida tourists that visit the Fort Jefferson National Monument. The monument had only 16,000 visitors in 1977 (Bureau of Economic and Business Research 1988).

In addition to their historical significance, the Dry Tortugas are notable for their unusual display of wildlife. Between May and September, thousands of terns come here to nest and rear their young (see **Chapter 9**). Frigatebirds, some with wing spans in excess of 2 m, follow the terns to this area and then rob the terns of their catches of fish (Tilden 1986).

National Wildlife Refuges and Wilderness Areas

The National Wildlife Refuge System is a network of refuges designed to preserve and enhance the natural ecosystems of endangered and threatened species and to provide habitat for migratory birds and other wildlife (Zaslowsky 1986). National Wilderness Areas are usually located within elements of the National Park System and represent regions that are to be maintained in an unspoiled state. The wilderness designation precludes permanent improvements and human habitation within these areas and generally results in these areas being relatively inaccessible.

The National Key Deer Refuge and Wilderness Area (*3*), covers Big Pine and Little Torch Keys, as well as several other keys and offshore islands. The refuge encompasses approximately 2,500 ha and provides protected habitat for approximately 300 endangered Key deer as well as 12 other endangered species (Kitching 1976; U.S. Fish and Wildlife Service 1986). The habitat is composed of mangrove swamps, salty marshes and flats, and forest land. Large numbers of seabirds and shorebirds use the refuge as a nesting site.

The Great White Heron National Wildlife Refuge and Wilderness Area (*4*) and the Key West National Wildlife Refuge and Wilderness Area (*5*) are composed of scattered islands and keys and the waters that lie between them. Together, these refuges cover over 3,800 ha, most of which is accessible only by boat. A portion of the Great White Heron Refuge overlaps the National Key Deer Refuge, providing double protection for the wildlife in that area. The major beneficiaries of these protected areas are the myriad seabirds and shorebirds that use these areas for nesting and feeding. The only nesting grounds in the U.S. of the Magnificent Frigatebird lie within the Key West Refuge (MCBCC 1986). The Wilderness designation of parts of the Great White Heron and Key West Refuges ensures that these areas will remain free from human development (Kitching 1976; National Park Service 1987).

Crocodile Lake National Wildlife Reserve (*7*) includes about 2,700 ha of watery and marshy terrain on the northern portion of Key Largo. The reserve was created to preserve one of the last habitats of the endangered American crocodile and includes the largest stand of tropical hardwood hammocks in the U.S. (MCBCC 1986). Several other endangered species including the Key Largo wood rat, the Key Largo cotton mouse, and the Shaus swallowtail butterfly inhabit the reserve as well (K. Fink, pers. comm. 1989, Florida Department of Community Affairs).

National Estuarine and Marine Sanctuaries

The purpose of the National Estuarine Sanctuaries program is to "create natural field laboratories in which to gather data and make studies of the natural and human processes occurring within the estuaries of the coastal zone" (FDNR 1981). There are currently 18 such reserves in the U.S. representing differing coastal and estuarine types.

Rookery Bay National Estuarine Sanctuary and Marine Preserve (*8*) is located just north of Marco Island in Collier County. The sanctuary and preserve cover approximately 1,150 ha and provide habitat for nesting birds as well as a variety of ground-dwelling estuarine animals and marine life (MMS 1986; Christie 1989). Over 80 species of birds have been observed here including several on the endangered species list.

The sanctuary and preserve are jointly owned and managed by Federal (National Oceanic and Atmospheric Administration [NOAA]), State (FDNR), and private agencies including Collier County Conservation Inc., The Nature Conservancy, and The National Audubon Society (K. Edwards, pers. corresp. 1989, Developmental Services Department, Collier County Government).

Currently, two regions of the study area hold the designation of National Marine Sanctuary. The first, Key Largo National Marine Sanctuary (*9*), covers roughly 26,000 ha of Atlantic waters. The sanctuary is adjacent to the John Pennekamp Coral Reef State Park (*10*) (**Figure 11.5**) and was designated a marine sanctuary in 1975 to preserve the coral reef ecosystem. Use of the sanctuary is restricted in an effort to maintain the health and viability of the reefs. The marine sanctuary designation generally prohibits the molestation or removal of any fauna, flora, or other resources from the sanctuary (Christie 1989).

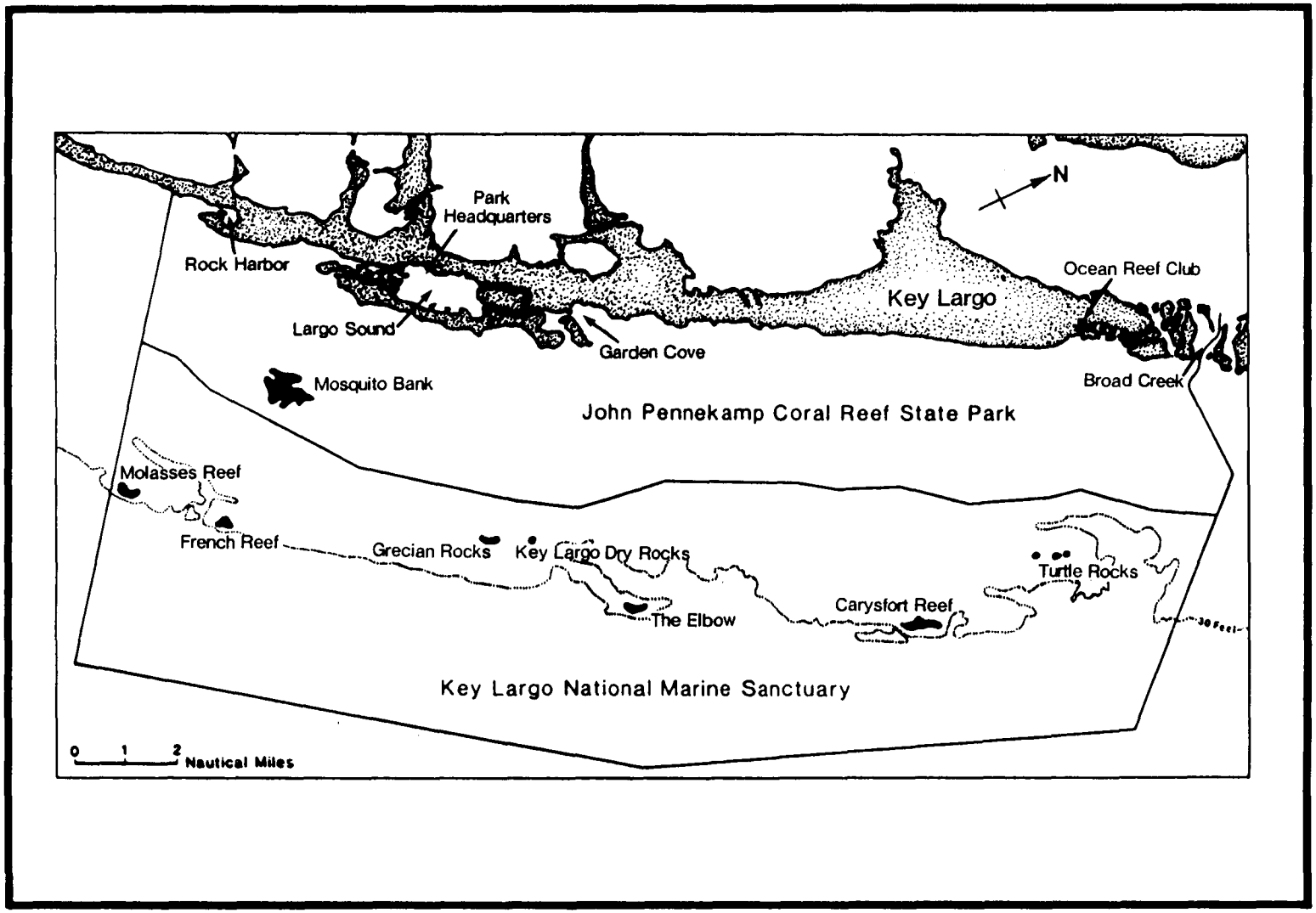

Figure 11.5. John Pennekamp Coral Reef State Park and the Key Largo National Marine Sanctuary and major reefs (From: Voss 1988).

Looe Key National Marine Sanctuary (*11*) covers 1,300 ha of Atlantic waters south of Big Pine Key. The protected area is composed of a coral reef and its surrounding waters and provides a special resource for educational and recreational uses. The wreck of the H.M.S. *Looe*, a British frigate that sank in 1744 (and for which the sanctuary is named), lies within the sanctuary's boundaries. Unusual water clarity and moderate sea conditions make Looe Key Sanctuary easy to view from the surface. Because of the wide range of water depths within the sanctuary, the reef is easily accessible to novice swimmers as well as experienced scuba divers (NOAA 1981).

State Parks and Recreation Areas

The State of Florida maintains a large and diverse inventory of parks and recreation areas. The best known of the Florida parks, John Pennekamp Coral Reef State Park (*10*), the first underwater park in the U.S., is located off Key Largo in Atlantic waters. The park covers roughly 31,000 ha, making it one of the larger parks in the country. It was established in 1963 in an effort to protect a portion of the only living coral reef system in the continental U.S. (Little 1987). Of the 52 varieties of coral found in the Atlantic reef community, 40 varieties can be found in the Park. In addition to the coral reef, the Park also provides a haven for an enormous variety of colorful reef fishes (Morris 1987).

John Pennekamp Coral Reef State Park is one of the State's busiest parks. Over 500,000 visitors used the park's facilities in 1987, with most engaging in snorkeling or scuba diving to view the reef (Bureau of Economic and Business Research 1988). The popularity of the park has strained the existing facilities, and concern has been expressed that overcrowding may deteriorate the park's ecological quality.

Collier Seminole State Park (*12*) covers 2,500 ha of mangrove swamp and tropical hardwood forests in the northern region of the study area. A 1,900-ha wilderness preserve is included in the park and provides an example of mangrove swamps as they would have appeared before Europeans arrived on the American continent. The wilderness preserve area can only be accessed by a lengthy canoe trip, and the number of visitors is limited each day (MMS 1986; Little 1987; K. Fink, pers. corresp. 1989). About 60,000 persons visit the park each year (Bureau of Economic and Business Research 1988).

Bahia Honda State Recreation Area (*13*) covers the bony skeleton of an ancient coral reef. The reef, now covered with dunes, beaches, and mangroves, plays host to a wide variety of plant and animal life including several threatened and endangered species. The recreation area covers Bahia Honda Key in the Lower Keys area and is accessible from U.S. Highway 1 or by water. In addition to the abundant wildlife found here, the recreation area contains outstanding beaches on both the Atlantic and Florida Bay sides (Little 1987; FDNR 1988a,b). Bahia Honda State Recreation Area is the southernmost recreation area in the U.S. and attracts over 300,000 visitors annually (MCBCC 1986; Bureau of Economic and Business Research 1988).

A little farther up the chain of keys lies Long Key, the site of Long Key State Recreation Area (*14*). This recreation area preserves a typical Florida Keys setting with extensive mangrove swamps and tropical hardwood hammocks. The shallow lagoons lining the key support a large marine population (FDNR 1988c). Even before the site was declared a State recreation area, Long Key was famous for the magnificent sport fishing in its surrounding waters (MCBCC 1986). Sport fishing continues to be one of the major reasons that over 100,000 persons visit the site annually (Bureau of Economic and Business Research 1988).

Historic Sites and Parks

Fort Zachary Taylor Park is located at the southwest point of Key West. The fort was built during the Civil War and is listed on the National Register of Historic Places. The fort offers a scenic view of the Atlantic Ocean and tours and historic presentations for the 140,000 annual visitors (Bureau of Economic and Business Research 1988; R. Vogeney, pers. corresp. 1989, City of Key West).

Indian Key State Historic Site covers about 4 ha of Indian Key. This location was the original seat of Dade County. Indian Key is accessible only by boat. Because of the isolated nature of this site, remains of the colony that first settled the island and was massacred by Seminole Indians still remain (MCBCC 1986). Approximately 5,000 persons visit the site annually (Bureau of Economic and Business Research 1988).

State Aquatic Preserves and Wildlife Sanctuaries

With the passage of the 1975 Aquatic Preserve Act, the Florida Legislature indicated the State's intention to preserve for the use of future generations those areas of submerged lands possessing exceptional qualities in their biological, aesthetic, or scientific characteristics. The Aquatic Preserve Act also provided uniform rules for the use of the preserves and prohibited uses such as dredging and filling, mining, drilling, and the erection of structures that could degrade the preserve's overall quality. Currently, 41 areas have received the aquatic preserve designation. Five of these preserves lie within the study area (FDNR 1986; Christie 1989).

- Rookery Bay National Estuarine Sanctuary and Marine Preserve (*8*) is also a State of Florida Aquatic Preserve. As noted earlier, parts of the Rookery Bay complex are owned and managed by Federal, State, and local conservation agencies, making it possible for Rookery Bay to fall under several preservation designations at once. The Rookery Bay Aquatic Preserve was established in 1977 and, along with the adjacent Cape Romano - Ten Thousand Islands Aquatic Preserve (*21*), encompasses 25,000 ha of the most pristine submerged lands in the State of Florida (FDNR 1988d).

- Cape Romano - Ten Thousand Islands Aquatic Preserve (*21*) lies to the southeast of the Rookery Bay National Estuarine Sanctuary and Marine Preserve and to the northwest of the Everglades National Park. The preserve covers approximately 11,300 ha of watery terrain dotted with small islands and fringed with mangrove forests. The Cape Romano - Ten Thousand Islands area was designated a State Aquatic Preserve in 1969 in an effort to protect this fragile ecosystem from encroaching agricultural and commercial-residential development. The preserve supports a wide variety of fish and wildlife, including the endangered West Indian manatee and American Bald Eagle (Klontz 1987).

- Coupon Bight Aquatic Preserve (*15*) is located off Coupon Bight in the Lower Keys. The preserve covers approximately 365 ha and affords protection to an area considered to contain unique biological and ecological characteristics.

- Lignumvitae Key Aquatic Preserve (*16*) is located in the Middle Keys and covers about 324 ha. Located on Lignumvitae Key itself are the Lignumvitae Botanical Gardens. These gardens are listed as a National Natural Landmark. The entire key is included in the botanical garden preserve and is maintained in the condition it appeared in 1919. A single structure, the Matheson House, exists on the key. Power is provided by a windmill, and water comes from a cistern. No more than 50 visitors are allowed at the site each day (MCBCC 1986).

- Biscayne Bay - Card Sound Aquatic Preserve (*17*) is located at the northern edge of the Florida Keys and in the southern portion of Biscayne Bay. The majority of this aquatic preserve lies within the bay area and falls under the jurisdiction of the Biscayne Bay National Park. As a result, the preserve is subject to joint management by State and Federal agencies.

Wildlife sanctuaries serve the same purpose as aquatic preserves except that the area of interest is generally not submerged. Two wildlife sanctuaries are located within the study area.

- Cowpens Key Wildlife Sanctuary (*18*) is located in the Middle Keys and provides a haven for several endangered and threatened species.

- Big Pine Key Wildlife Sanctuary (*19*) covers a portion of Big Pine Key and provides habitat for the endangered Key deer. Together with the National Key Deer Wildlife Reserve, the Big Pine Key Sanctuary supports the 300 Key deer living on Big Pine Key. In addition to providing habitat for the Key deer, the sanctuary also supports a wide variety of bird life.

Florida Archeological Reserves

The State of Florida has designated four broad areas of State territorial waters as archeological reserves. In these areas, no salvage operations will be approved, and the areas will be used exclusively for research by qualified institutions. One such archeological reserve is located in the study area, at Indian Key State Park near Islamorada, off the southeastern coast of Key Largo (*20*) (Christie 1989). The preserve is developed around the remains of the *San Pedro*, a vessel of the 1733 Spanish fleet that wrecked in a hurricane off the coast.

County Parks, Recreation Areas, and Beaches

A complete listing of county and local park, recreation, and beach facilities in the area would entail numerous entries. However, some of these holdings are of particular interest due to their locational/recreational characteristics. The following parks contain beach areas or shoreline mangrove regions of particular interest to this study (Univ. of West Florida 1985; R. Vogeney, pers. corresp. 1989).

- Harry Harris County Park (Monroe) contains 75 m of Atlantic beach on Key Largo.

- Upper Matecumbe County Park (Monroe) has 61 m of Atlantic beach on Upper Matecumbe Key.

- Switlick County Park/Marathon Recreation Complex (Monroe) has 61 m of beach on Marathon Key.

- Little Duck Key County Park (Monroe) has 425 m of ocean frontage on Little Duck Key.

- George Smathers Beach (City of Key West) has 1,200 m of developed beach on Key West.

- Clarence Higgs Memorial Beach (Monroe County) has 91 m of developed Atlantic beach on Key West.

- South Beach (City of Key West) has a small beach area that includes a public access pier on Key West.

- Simonton Beach (City of Key West) has a small beach with parking area on Key West.
- Vernon Street Beach (City of Key West) has a small beach area on Key West.

National Register Sites

The following locations within the study area are currently designated as, or qualify as, National Register Sites (MMS 1986; FDNR 1987a).

Collier County:	Marco Island Archeological Sites
Monroe County:	Fort Jefferson National Monument
Key West:	Fort Zachary Taylor Eduardo H. Gato House Ernest Hemingway House Key West Historic District Little White House (Quarters A) Key West Historic District (Extension) Martello Gallery-Key West Art and Historical Museum Old Post Office and Custom House Dr. Joseph Y. Porter House Sand Key Lighthouse Schooner Western Union The Armory U.S. Coast Guard Headquarters, Key West Station U.S. Naval Station West Martello Tower
Sugarloaf Key:	Bat Tower
Other Sites:	Indian Key San Jose Shipwreck Site Rock Mound Archeological Site Carysfort Lighthouse John Pennekamp Coral Reef State Park and Reserve Overseas Highway and Railroad Bridges

Outstanding Florida Waters

Florida Statutes 403.06(27)(a) authorize the Florida Department of Environmental Regulation (FDER) to create a category of waters to be considered for special protection. That category, Outstanding Florida Waters, provides for protection against degradation of water quality in selected areas. The statutes require that direct discharge of pollutants cannot lower existing water quality and indirect discharges must not significantly lower existing water quality. Dredging and filling operations in these areas must be shown to be in the public interest before permits will be issued. This stipulation precludes projects that adversely affect (1) human health, (2) the conservation of fish and wildlife, and (3) the fishing or recreational values of marine productivity in the vicinity of the project (FDER 1988a).

The FDER has undertaken, as a matter of policy, to incorporate in the designation of Outstanding Florida Waters, those areas that fall under the designation of (1) National parks, (2) wildlife refuges, (3) National seashores, (4) estuarine and marine sanctuaries, (5) State parks, (6) wilderness areas, and (7) aquatic preserves. In addition, any areas the FDER considers to be of exceptional recreational or ecological value may be designated as Outstanding Florida Waters. The following regions of the study area are designated Outstanding Florida Waters.

- Biscayne National Park
- Everglades National Park
- Crocodile Lake National Wildlife Reserve
- Great White Heron National Wildlife Refuge and Wilderness Area
- Key West National Wildlife Refuge and Wilderness Area
- National Key Deer Wildlife Reserve
- Bahia Honda State Recreation Area
- Collier-Seminole State Park
- John Pennekamp Coral Reef State Park
- Long Key State Recreation Area
- Lignumvitae Key Aquatic Preserve
- Biscayne Bay - Card Sound Aquatic Preserve
- Cape Romano - Ten Thousand Islands Aquatic Preserve
- Coupon Bight Aquatic Preserve
- Rookery Bay Aquatic Preserve
- Key Largo National Marine Sanctuary
- Looe Key National Marine Sanctuary

In addition to the above, the FDER applies the designation to areas purchased under the Environmentally Endangered Lands (EEL) bond program, Conservation and Recreation Lands (CARL) program, Land Acquisition Trust Fund (LATF) program, and the Save Our Coast (SOC) program. The North Key Largo hammock region falls under these programs and holds the Outstanding Florida Waters designation.

With its authority to designate as Outstanding Florida Waters any waters that are of exceptional recreational or ecological significance, the FDER has chosen to include under this designation the entire Florida Keys area, including any channels in the region and encompassing nearly all of the Florida jurisdictional waters surrounding the Keys. A small area around the Key West sewage outfall, and a small area around the Stock Island power plant mixing zone are exempt from the designation as are all artificial water bodies created in the region (Christie 1989; FDER 1989).

Areas of Critical State Concern

The State of Florida designates as Areas of Critical State Concern those regions in which the State perceives a significant threat to a valuable State resource. The Florida Keys are designated as an Area of Critical State Concern. This designation results in careful evaluation by the State of all development within the affected region. Legislative guidelines for development within the Florida Keys Area of Critical State Concern require that the Florida Keys comprehensive plan, and any changes in the plan must protect coral reef growth and viability (Christie 1989).

Other rules governing Areas of Critical State Concern restrict the dredge and fill permitting process and prohibit the taking of coral under all but a few special circumstances. The Florida State Legislature created the Area of Critical State Concern Trust Fund to be used as a source of funds for the rehabilitation of injured and stressed coral reefs and other natural resources (Christie 1989).

The Big Cypress Preserve, Fakahatchee Strand, and Cape Romano - Ten Thousand Islands region have also been designated as Areas of Critical State Concern. Contamination and diversion of waters from the Everglades watershed is threatening the long term viability of that ecosystem. The designation ensures that new development and existing agricultural activities must comply with State guidelines for the protection of the Everglades watershed (K. Edwards, pers. corresp. 1989).

Proposed Acquisitions

The State of Florida operates an aggressive group of land acquisition programs. The EEL, CARL, LATF, and SOC programs all work to identify and acquire outstanding Florida lands for preservation. Several sites in the study area have recently been designated of special interest, and efforts to acquire those areas have begun. Under the CARL program, the North Key Largo Hammocks botanical area has been identified as a high priority site, as have the Windley Key quarry area, the Key West Salt Ponds, Cutty Hammock, North Layton Hammock, Tropical Hammocks of the Redlands, and the Deering Estate Addition. Under the CARL program, the State is actively seeking to add lands to already established conservation areas such as the Rookery Bay complex, Fakahatchee Strand, and Coupon Bight (Partington 1987; Land Acquisition Selection Committee 1989).

Matecumbe beach contains about 250 m of Atlantic ocean frontage and is backed by a lush vegetation zone. This area of Upper Matecumbe Key is currently a high priority acquisition under both the SOC and LATF programs.

The Federal government also continues to explore the acquisition of additional lands in the study area. Recently, the USDOI expressed a willingness to consider for National park status, an area encompassing the Dry Tortugas and the Marquesas Keys (State of Florida, Office of the Governor 1989a). In late 1989, the Federal government joined with the State of Florida in acquiring the East Everglades adjoining Everglades National Park.

Private preservation associations are also active in the study area. The Florida Chapter of The Nature Conservancy has begun what is called the Florida Keys initiative. This program seeks to raise $5 million for the acquisition of sensitive habitat in the Florida Keys. In the past nine months, seven transactions have been completed, with the most recent acquisition preserving a portion of Little Torch Key critical to the survival of the Key deer (The Nature Conservancy 1989). Properties purchased by The Nature Conservancy are often turned over to State or Federal agencies to be managed and maintained in the public interest.

CONCLUSIONS

Current land use patterns in the three-county area reflect the unique and environmentally sensitive nature of the region. The vast majority of these lands are designated as parks or preserves. Because so little of the land within the study area is subject to development, population densities in a few highly developed coastal regions (metropolitan Miami, Key West, and the Naples area) are high.

Water resources in the study are limited. Only within Collier County could a large new supply of water (non-potable) be developed for use in OCS activities. However, there are no ports in Collier County with the capacity to serve as an OCS supply base.

None of the larger ports near the study area could serve effectively as a supply base for OCS operations. The oil industry has previously used Port Manatee (in Tampa Bay) as a temporary supply base for exploratory operations on the Southwest Florida shelf north of the study area, but would most likely locate any permanent supply base outside the State of Florida.

Marine-based industries that might be affected by OCS developments in the study area contribute significantly to their local economies. The Statewide economic impact of commercial fishing in the study area is estimated to be $220 million, while the economic impact of recreational fisheries is about $1.2 billion (1987 dollars). This amounts to about 0.5% of Gross State Product in 1987.

About 18% of all tourist visits within Florida occur in the study area. In total (including the recreational fisheries impacts noted above), this tourism generated approximately 3.5% of Gross State Product in recent years (or about $6.2 billion annually).

No conflicts in use are expected between OCS developments in the study area and marine mining of phosphates (because this type of mining is currently uneconomic) or military uses of the area (because of stipulated agreements between the USDOI and the military services).

There are no major sociological studies of the impact of OCS development on Florida communities. Other studies (such as those relating to the social impacts of new residential developments in Key West, or of the sociology of small fishing communities in Florida) may provide useful insights on these issues, however.

The economic data needed to evaluate the costs and benefits of OCS development in the study area are marginally adequate and could be improved at a moderate cost if four areas of research were pursued in the future, as outlined below.

- **Employment information for the fishing industry** is currently included in the "agricultural services" category in State labor force records. A more detailed breakdown of employment data focusing on commercial fisheries alone at both the State and county levels would make it possible to isolate any future impacts on this sector relating to OCS activities.

  Similarly, employment information for the tourism sector is now measured very broadly as total employment in tourism-related businesses such as restaurants, hotels, and amusement parks. This approach includes sales to local residents and businesses and thus tends to exaggerate the economic impact of tourism. This problem could be eliminated through a sampling program designed to identify the true tourism component of sales.

- **Commercial fisheries reports** currently identify catches only by landing site and not by location of catch. If OCS grid location of catch were also required to be reported, this would permit more accurate analyses of any future conflicts between commercial fishing and OCS development.[1]

- **Recreational fishing and other tourism data** could be greatly improved if the surveys used to measure participation and expenditures by tourists were increased in size to permit extrapolation of the findings to individual counties. The questions could also be designed to identify the economic benefits yielded by overlapping uses such as beach visits, swimming, boating, and fishing individually. In addition, present State tourism surveys make no attempt to evaluate the user value (or consumer's surplus) yielded by Florida's beaches, coral reefs, and waters. Contingent valuation methods could be used on an occasional basis to focus in on this important aspect of resource valuation.

[1]The FDNR currently obtains some fisheries data in the Gulf of Mexico by area of catch (R. Muller, pers. comm. 1990, FDNR, St. Petersburg). This information is provided on a voluntary basis only, by a limited number of boats, and the location method used is not specific enough for detailed analyses to be made of the data.

- **Indirect or non-use values yielded by environments of critical concern** in the study area, such as coral reefs and mangrove communities, cannot be estimated reliably with existing data. Estimating "preservation," "existence," and "option" values for these environments would require new and carefully-designed surveys to be carried out among samples of the State and National populations. While there is still disagreement among economists, lawyers, and public policy makers concerning the meaning and validity of these non-use categories of value (and their comparability to traditional use values), additional research in this area is clearly warranted.

REFERENCES CITED

Bell, F. W., and V. R. Leeworthy. 1986. *An economic analysis of the importance of saltwater beaches in Florida.* Florida Sea Grant Program Rep. No. 82. Gainesville: Univ. of Florida.

Bell, F. W., and V. R. Leeworthy. 1988. *Recreational demand for saltwater beach days.* Florida Sea Grant Project No. R/C-P-12. Gainesville: Univ. of Florida.

Bell, F. W., P. E. Sorensen, and V. Leeworthy. 1982. *The economic impact and valuation of saltwater recreational fisheries in Florida.* Florida Sea Grant Program Rep. No. 47. Gainesville: Univ. of Florida.

Bureau of Economic and Business Research, College of Business Administration, University of Florida. 1988. *1988 Florida statistical abstract*, 22nd edition, ed. A. H. Shoemyen. Gainesville: The Univ. Presses of Florida.

Bureau of the Census. 1988. *Statistical abstract of the United States: 1988.* 108th edition. Washington, DC: U.S. Government Printing Office.

Bureau of the Census. 1989a. *Statistical abstract of the United States: 1989.* 109th edition. Washington, DC: U.S. Government Printing Office.

Bureau of the Census. 1989b. *Population profile of the United States: 1989.* Washington, DC: U.S. Government Printing Office.

Cato, J. C. 1985. An overview of the economics of fisheries and habitat in Florida. In *Florida aquatic habitat and fisheries resources*, ed. W. Seaman, Jr. Kissimmee: American Fisheries Society, Florida Chapter.

Cato, J. C. 1989. Statement to the presidential outer continental shelf leasing and development task force, 15 June 1989, Miami, FL.

Christie, D. S. 1989. *Florida's ocean future: Toward a State ocean policy.* Tallahassee: Governor's Office of Planning and Budgeting.

Collier County Growth Planning Department. 1989. *Collier County growth management plan. Future land use element.* Naples, FL.

Collier County Utilities Division. 1989. *Collier County comprehensive plan. Potable water sub-element.* Naples, FL.

Curtis, T. D., and E. W. Snows. 1984. *A comparative study of the social and economic benefits of artificial beach nourishment--civil works in Northeast Florida.* Florida Department of Natural Resources, Beaches and Shores STAR Rep. No. 84-1.

Curtis T. D., E. W. Snows, and J. G. Spence. 1980. *The economic importance of the beaches of Florida to the State's economy: A case study of Ft. De Soto Park.* Florida Department of Natural Resources, Beaches and Shores STAR Rep. No. 82-1.

Ellerbrock, M. J., and J. W. Milon. 1984. *A methodology for estimating the economic impact of sportfishing tournaments.* Florida Sea Grant Program Rep. No. 59. Gainesville: Univ. of Florida.

Fernald, E. A. 1981. *Atlas of Florida.* Tallahassee: The Florida State Univ. Foundation, Inc.

Florida Department of Commerce. 1985a. *European travel study 1984.* Tallahassee: Department of Commerce, Division of Tourism.

Florida Department of Commerce. 1985b. *Vacation habits of Floridians.* Tallahassee: Department of Commerce, Division of Tourism.

Florida Department of Commerce. 1988a. *Florida county profile 1988, Collier County.* Tallahassee: Department of Commerce, Division of Economic Development, Bureau of Economic Analysis.

Florida Department of Commerce. 1988b. *Florida county profile 1988, Monroe County.* Tallahassee: Department of Commerce, Division of Economic Development, Bureau of Economic Analysis.

Florida Department of Commerce. 1988c. *Florida county profile 1988, Dade County.* Tallahassee: Department of Commerce, Division of Economic Development, Bureau of Economic Analysis.

Florida Department of Commerce. 1988d. *Florida visitor study 1987 - Executive summary.* Tallahassee: Department of Commerce, Division of Tourism.

Florida Department of Commerce. 1988e. *Florida county comparisons 1988.* Tallahassee: Department of Commerce, Division of Economic Development.

Florida Department of Commerce. 1988f. *Visitor survey-county data.* Unpubl. data.

Florida Department of Commerce. 1989. *Visitor study 1988.* Draft version, pre-publication.

Florida Department of Environmental Regulation. 1988a. *Factsheet about outstanding Florida waters.* Informational pamphlet.

Florida Department of Environmental Regulation. 1988b. Personal correspondence dated 14 December 1988 from Randall L. Armstrong, director of the Division of Water Management to Kent E. Stouffer, U.S. Department of Interior, Mineral Management Service.
Florida Department of Environmental Regulation. 1989. *Water quality standards*. Tallahassee: Department of Environmental Regulation.
Florida Department of Natural Resources. 1981. *Rookery Bay National Estuarine Sanctuary*. Informational pamphlet.
Florida Department of Natural Resources. 1986. *Aquatic preserves of Southwest Florida*. Informational pamphlet.
Florida Department of Natural Resources. 1987a. *Outdoor recreation in Florida - 1987*. Tallahassee: Department of Natural Resources, Division of Recreation and Parks.
Florida Department of Natural Resources. 1987b. *1986 National recreational boating facility inventory*. Tallahassee: Department of Natural Resources.
Florida Department of Natural Resources. 1988a. *Bahia Honda State Recreation Area*. Informational pamphlet.
Florida Department of Natural Resources. 1988b. *Vertebrates identified in Bahia Honda State Recreation Area*. Informational pamphlet.
Florida Department of Natural Resources. 1988c. *Long Key State Recreation Area*. Informational pamphlet.
Florida Department of Natural Resources. 1988d. *Rookery Bay and Cape Romano-Ten Thousand Islands aquatic preserves management plan*. Tallahassee: Department of Natural Resources, Division of State Lands, Bureau of Aquatic Preserves.
Florida Department of Natural Resources. 1989. *Outdoor recreation in Florida - 1989*. Tallahassee: Department of Natural Resources, Division of Recreation and Parks.
Howard Publications, Inc. 1977. *South Florida ports handbook*. Jacksonville: Howard Publications, Inc.
Kitching, J. 1976. *Birdwatcher's guide to wildlife sanctuaries*. New York: Arco Publishing Company Inc.
Klontz, S. W. 1987. Florida's aquatic preserves. *Fla. Environ. Urb. Iss.* 15(1):14-18.
Land Acquisition Selection Committee. 1989. Ranking sheet for the 1989 CARL annual priority list. Informational printout dated December 1989. Tallahassee.
Little, M. 1987. *Camper's guide to Florida*. Houston: Gulf Publishing Company.
Martinez, R. 1989. Statement to the OCS presidential task force, 12 June 1989, Tallahassee, FL.
Metro Dade County Planning Department. 1988a. *Comprehensive development master plan. Water, sewer and solid waste element*. Miami.
Metro Dade County Planning Department. 1988b. *Comprehensive development master plan. Conservation, aquifer recharge and drainage element*. Miami.
Metro Dade County Planning Department. 1988c. *Comprehensive development master plan. Land use element. Support components*. Miami.
Milon, J. W., and C. M. Adams. 1987. *The economic impact of Florida's recreational boating industry in 1985*. Florida Sea Grant Program Tech. Pap. No. 50. Gainesville: Univ. of Florida.
Milon, J. W., W. D. Mulkey, P. H. Riddle, and G. H. Wilkowske. 1983a. *Economic impact of marine recreational boating on the Florida economy*. Florida Sea Grant Program Rep. No. 54. Gainesville: Univ. of Florida.
Milon J. W., G. H. Wilkowske, and G. L. Brinkman. 1983b. *Financial structure and performance of Florida's recreational marinas and boatyards: A report on financial and operating ratios for 1979 through 1981*. Florida Sea Grant Program Rep. No. 53. Gainesville: Univ. of Florida.
Minerals Management Service. 1986. *Visual No. 3E, recreation and multiple use, for draft environmental impact statement. Proposed oil and gas lease sales 113/115/116*. New Orleans: U.S. Department of the Interior, Minerals Management Service.
Minerals Management Service. 1987. *Final environmental impact statement. Proposed oil and gas lease sale 113/115/116*. OCS EIS MMS 87-0019. New Orleans: U.S. Department of the Interior, Minerals Management Service.
Minerals Management Service. 1989a. *Gulf of Mexico sales 123 and 125: Central and Western Planning Areas. Final environmental impact statement*. OCS EIS/EA MMS 89-0053. New Orleans.
Minerals Management Service. 1989b. *OCS national compendium*. MMS 89-0043. Herndon, VA: U.S. Department of the Interior, Minerals Management Service.
Monroe County Board of County Commissioners. 1986. *Florida Keys' comprehensive plan, Vol. 1*. Tallahassee: State of Florida Department of Community Affairs and the Administration Commission.
Morris, A. 1987. *The Florida handbook*. Tallahassee: Peninsular Publishing Company.
National Marine Fisheries Service. 1987. *Fisheries of the United States, 1986*. Washington, DC: U.S. Government Printing Office.
National Marine Fisheries Service. 1988. *Annual landings summary 1977-1987*. Unpubl. data.
National Oceanic and Atmospheric Administration. 1981. *Looe Key National Marine Sanctuary*. Informational pamphlet.
National Oceanic and Atmospheric Administration. 1985. *Gulf of Mexico coastal and ocean zones strategic assessment: Data atlas*. Pre-publication edition.
National Park Service. 1987. *The National parks: Index 1987*. Washington, DC: U.S. Government Printing Office.
Otwell, W. S., J. Bellairs, and D. Sweat. 1984. *Initial development of a deep-sea crab fishery in the Gulf of Mexico*. Florida Sea Grant Program Rep. No. 61. Gainesville: Univ. of Florida.
Partington, W. M. Jr. 1987. *An official's guide to Florida environmental issues 1987*. prepared for The Florida Conservation Foundation,Inc. Winter Park, FL: The Florida Conservation Foundation Inc.

Pompe, J. 1990. An application of the hedonic method to analyze marina pricing in Florida. Ph.D. diss., Florida State Univ.

Rockland, D. B. 1988. *The economic impact of the sport and commercial fisheries of the Florida Keys*. Prepared for Everglades Protection Association, Florida Conservation Association, Monroe County Industrial Development Authority.

South Florida Regional Planning Council. 1977. *Socio-economic overview of the Port of Key West, the Port of Miami, Port Everglades, the Port of Palm Beach and the Port of Fort Pierce*. Hollywood, FL.

South Florida Regional Planning Council. 1984a. *Marina siting survey*. Hollywood, FL.

South Florida Regional Planning Council. 1984b. *OCS facility siting study*. Hollywood, FL.

State of Florida, Office of the Governor. 1988. Press release dated 26 May 1988. Tallahassee.

State of Florida, Office of the Governor. 1989a. Personal correspondence with Manuel Lujan, Jr. Secretary of the Department of the Interior, dated 6 March 1989.

State of Florida, Office of the Governor. 1989b. Press release dated 9 February 1989. Tallahassee.

The Nature Conservancy. 1989. *Florida chapter news*. Winter Park, FL: The Nature Conservancy, Florida Chapter.

Tietenberg, T. 1988. *Environmental and natural resource economics*, 2nd edition. Glenview: Scott, Foresman, and Co.

Tilden, F. 1986. *The National parks*. New York: Alfred A. Knopf Inc.

United Nations Educational, Scientific, and Cultural Organization. 1982. *A legacy for all*. Paris.

U.S. Fish and Wildlife Service. 1986. *Preliminary survey of contaminant issues of concern on National Wildlife Refuges*. Washington, DC: U.S. Government Printing Office.

University of West Florida. 1985. *Florida's sandy beaches: An access guide*. Gainesville: Univ. Presses of Florida.

Voss, G. L. 1988. *Coral reefs of Florida*. Sarasota: Pineapple Press.

Waterways Cruising Club, Inc. 1988. *Florida cruising directory*. Stuart, FL.

Zaslowsky, D. 1986. *These American lands*. New York: Henry Holt and Company Inc.

CHAPTER 12
OFFSHORE OIL AND GAS OPERATIONS IN SOUTH FLORIDA: HISTORY, STATUS, AND POTENTIAL ENVIRONMENTAL EFFECTS

Neal W. Phillips

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INTRODUCTION

The purpose of this chapter is to provide an overview of offshore oil and gas operations that might occur if leasing proceeds in South Florida. The history of leasing and exploratory drilling in and near the study area is reviewed. An overview of the phases of offshore operations is presented, with discussions of environmental concerns. Potential effects of routine operational discharges and accidental oil spills are treated in detail in **Chapters 13, 14,** and **15.** Socioeconomic costs and benefits of offshore oil and gas development are evaluated in **Chapter 16.**

HISTORY OF OFFSHORE LEASING AND DRILLING IN SOUTH FLORIDA

Offshore oil exploration in South Florida began in the late 1940s, following the discovery of oil onshore at Sunniland in 1943 (Montgomery 1987). Seventeen exploratory wells were drilled between 1946 and 1967, either on land in the Florida Keys or in shallow, coastal waters (**Table 12.1**). The latter were on either Federal or State lease blocks. After a hiatus, 11 more wells were drilled between 1974 and 1986 on Federal lease blocks in deeper waters of the Southwest Florida shelf between Tampa and Naples. In recent years, industry interest has shifted to Federal waters of the continental shelf south of Naples, where the Federal government granted 73 leases in 1984 and 1985. However, because of strong opposition by the State of Florida, it is unclear whether further leasing will occur or whether proposed exploratory drilling on the existing leases will be allowed to proceed.

Early Leasing and Exploration

The State of Florida began leasing offshore waters for oil and gas exploration in 1941 (McKenzie 1983). At one time, nearly all of Florida's Gulf coastal waters were under lease (**Figure 12.1**). Coastal Petroleum Co. holds the two remaining active leases, which consist of the outer third of leases 224-A and 224-B shown in **Figure 12.1**. Under a 1976 agreement between the State and Coastal Petroleum Co., the leases will expire in 2016 (McKenzie 1983).

Between 1946 and 1967, nine exploratory wells were drilled in State waters in or near the study area (**Table 12.1**). Elsewhere in State waters, a well has been drilled as recently as 1983. Current State policy prohibits oil and gas drilling in State waters (D. Tucker, pers. comm. 1990, State of Florida, Office of the Governor).[1]

A Federal lease sale held in 1959 has been the only offering of blocks in the Florida Keys area. Eighty blocks were put up for bid, 23 were leased, and three exploratory wells were drilled near the Marquesas Keys in 1960 and 1961 (**Table 12.1**) (La Liberte and Harris 1987). Some leases reverted to the State in 1961 as a result of a Supreme Court decision concerning territorial waters.

Drilling activity in and near the study area between 1946 and 1967, on both Federal and State leases, can be summarized as follows. Seventeen exploratory wells were drilled, either on land in the Florida Keys or in shallow, South Florida coastal waters (**Table 12.1**). Well locations are shown on **Figure 12.2**. The wells fall into several groups:

- Four wells were drilled in the Upper Keys (Key Largo and Plantation Key) between 1946 and 1953: two on land and two in shallow water.
- Three wells were drilled on land in the Lower Keys between 1947 and 1959: one on Sugarloaf Key and two on Big Pine Key.
- One well was drilled on a Federal lease near Cape Sable in 1955.

[1] A settlement agreement for the Coastal Petroleum Co. lease requires that drilling be conducted at least once every five years. Because no minimum depth is specified, the State has allowed Coastal Petroleum Co. to satisfy this requirement by taking geological core samples (D. Tucker, pers. comm. 1990).

Table 12.1. Exploratory wells drilled in South Florida nearshore waters and on land in the Florida Keys [Compiled from: Smith and Hunt (1979), Attilio and Blake (1983), Applegate and Lloyd (1985), Shinn et al. (1989b), and unpublished data supplied by E. Shinn and the Florida Bureau of Geology].

Date	Lease/Block*	Operator	Location	Water Depth (m)	Comments
1946	---	Republic-Robinson	Key Largo	?	Shows of heavy, black oil; slight show of gas
1947	FSL 373	Gulf	Big Pine Key	(on land)	Oil-stained cuttings
1947	FSL 374	Gulf	Sugarloaf Key	(on land)	
1949	FSL 363	Coastal	Plantation Key	?	
194?	---	Coastal-Williams	Key Largo	(on land)	
1953	---	Sinclair-Williams	Key Largo	(on land)	
1955	FSL 826-G	Gulf	Cape Sable	3.7	Oil stained core
1959	FSL 826-Y	Gulf	Marquesas Keys	4.5-5.5	Show of oil
1959	FSL 1011	California	Big Pine Key	(on land)	Show of oil
1960	FSL 224B	California-Coastal	offshore Ft. Myers	?	
1960	OCS Block 28	Gulf-California	Marquesas Keys	11-12	Show of oil
1961	FSL 224A	California-Coastal	offshore Ft. Myers	?	
1961	OCS Block 44	Gulf-California	Marquesas Keys	20	
1961	FSL 1011	California	Marquesas Keys	4.5	
1961	OCS Block 46	Gulf-California	Marquesas Keys	23	
1962	FSL 1011	California	Marquesas Keys	4.5	
1967	FSL 224B	Mobil	offshore Ft. Myers	?	

* FSL = Florida State Lease. OCS = Outer Continental Shelf (Federal lease from 1959 sale).

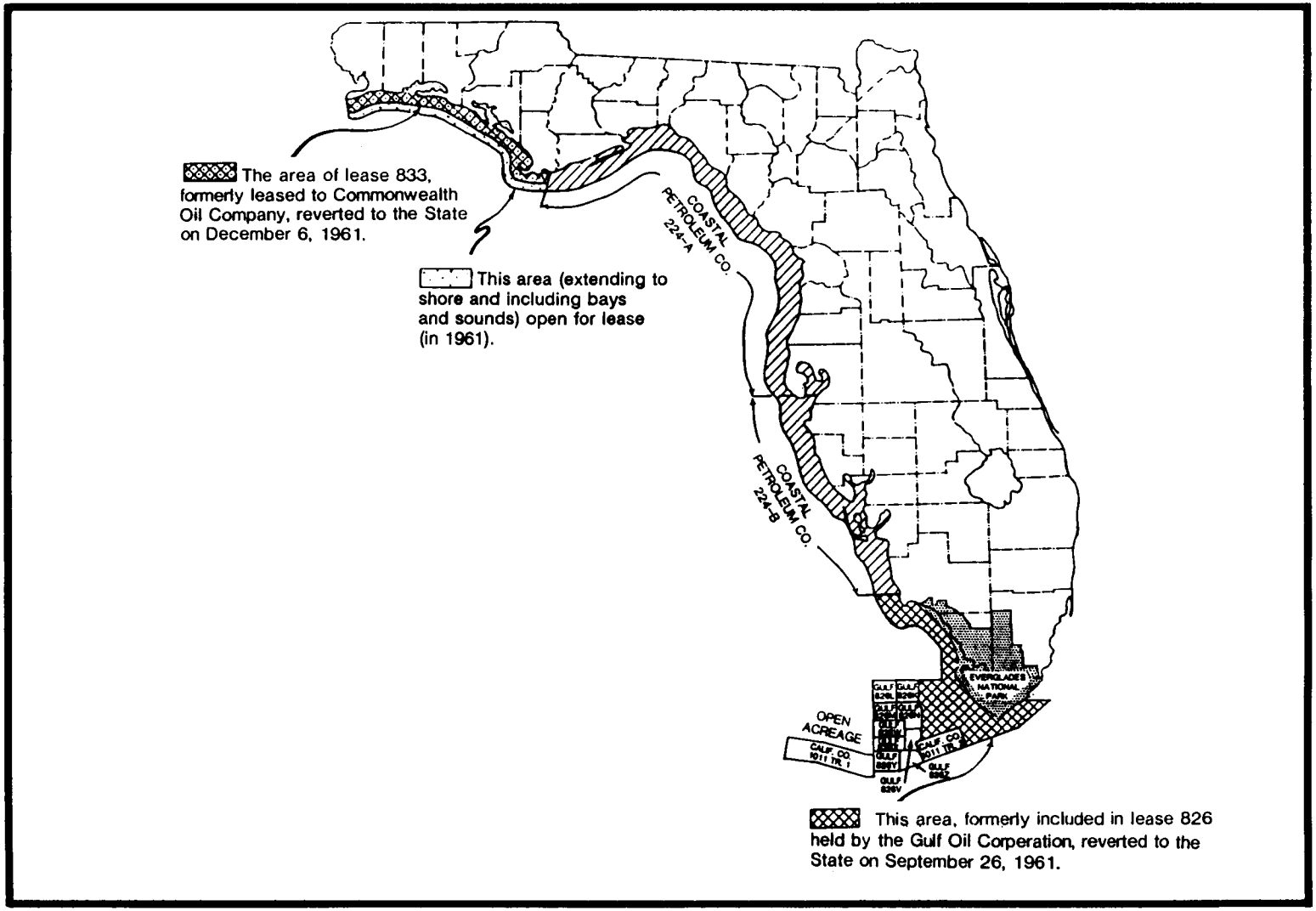

Figure 12.1. State of Florida offshore oil and gas leasing map as of 31 December 1961 (From: Babcock 1962). Only the outer third of the two Coastal Petroleum Co. leases is still active.

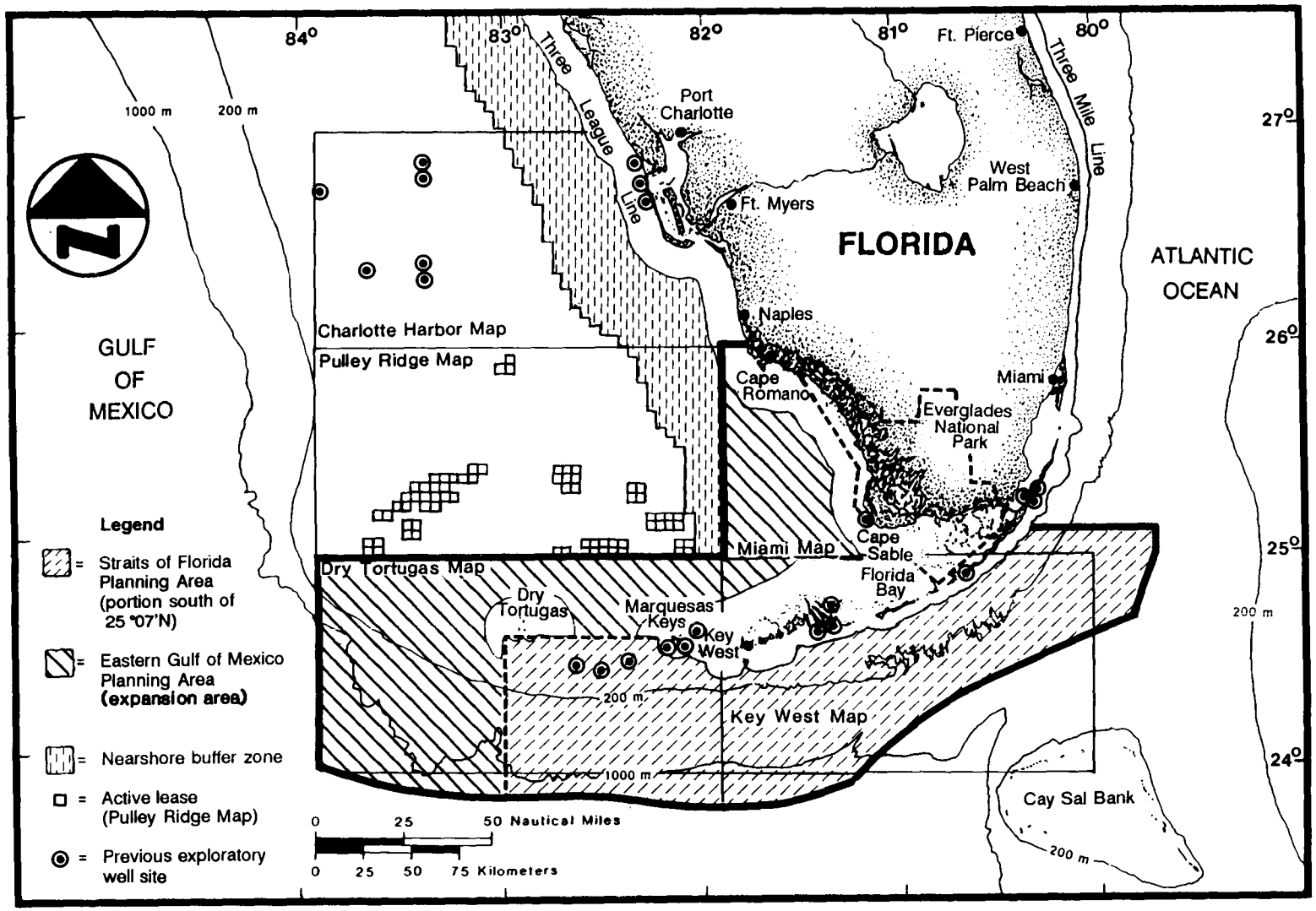

Figure 12.2. Leasing boundaries, active leases, and previous exploratory well sites in and near the study area.

- Six wells were drilled in the vicinity of the Marquesas Keys between 1959 and 1962. Three were on Federal leases, and three on State leases. Two of the wells were potential low-volume oil producers in the Sunniland Formation (Applegate and Lloyd 1985, Appendix II).

- Three wells were drilled in State waters off Ft. Myers in 1960, 1961, and 1967.

One of the exploratory well sites at the Marquesas Keys was visited in 1979 by scientists from the Bureau of Land Management (Smith and Hunt 1979). All six well sites at the Marquesas Keys were visited recently as part of a Minerals Management Service (MMS) project designed to evaluate the effects of exploratory drilling on South Florida benthic communities (Shinn et al. 1989). Results of those surveys are discussed later in this chapter.

Recent Leasing and Exploration

Portions of the Eastern Gulf of Mexico Planning Area south of Tampa have been offered for lease during several Federal lease sales in the late 1970s and 1980s. Lease sales prior to May 1983 were held using a "tract selection" approach, under which a few dozen to a few hundred blocks of known industry interest were offered. In lease sales through March 1983, 68 blocks were leased in four map areas south of Tampa (St. Petersburg, The Elbow, Charlotte Harbor, and Vernon Basin). All of the leases were north of 26° N. Eleven exploratory wells were drilled in these areas between 1974 and 1986, including six in the Charlotte Harbor map area (MMS 1988a) (**Figure 12.2**). No commercial finds have been reported, and the leases have since expired.

In May 1983, the Federal government began offering large areas including thousands of blocks in each lease sale. The first two eastern Gulf of Mexico sales to use this "area-wide" approach were Sale 79 (January 1984) and Sale 94 (December 1985). These were also the first lease sales to include blocks in the Pulley Ridge and adjacent Howell Hook map areas, south of 26° N. Currently, there are 70 active leases in the Pulley Ridge area and three in the Howell Hook area. There has been no leasing of blocks south of 25° N in the Dry Tortugas, Key West, and Miami map areas; these blocks were not part of any planning area at the time of the 1984 and 1985 lease sales.

Under the 5-Year Outer Continental Shelf Oil and Gas Leasing Program (hereafter referred to as the 5-Year Program), a lease sale (116) scheduled for November 1988 was originally to include blocks south of 26° N (MMS 1987a). However, in June 1988, the sale was split into two parts. Part I, which was held on schedule, included mostly blocks north of 26° N; some blocks south of 26° N and west of 86° W were offered, but none were leased. Part II, which was to include blocks south of 26° N and east of 86° W (**Figure 12.3**), was to be held no earlier than March 1989 but subsequently has been postponed indefinitely (see below).

The State of Florida has consistently objected to leasing on the Southwest Florida shelf south of 26° N, and the possibility of exploratory drilling on the 73 active leases there has been postponed several times. A 1984 Congressional moratorium prohibited exploratory drilling south of 26° N until three years of MMS environmental studies were completed. The studies were completed in 1987, and plans of exploration (POEs) were filed by two Pulley Ridge area leaseholders in 1988 and subsequently approved by the MMS. However, the State of Florida found the POEs inconsistent with its Federally approved Coastal Zone Management (CZM) program, citing mainly the potential consequences of a catastrophic oil spill (Twachtmann 1988). Appeals for an override of the consistency denial from the two leaseholders are currently under review by the Secretary of Commerce (D. Tucker, pers. comm. 1990).

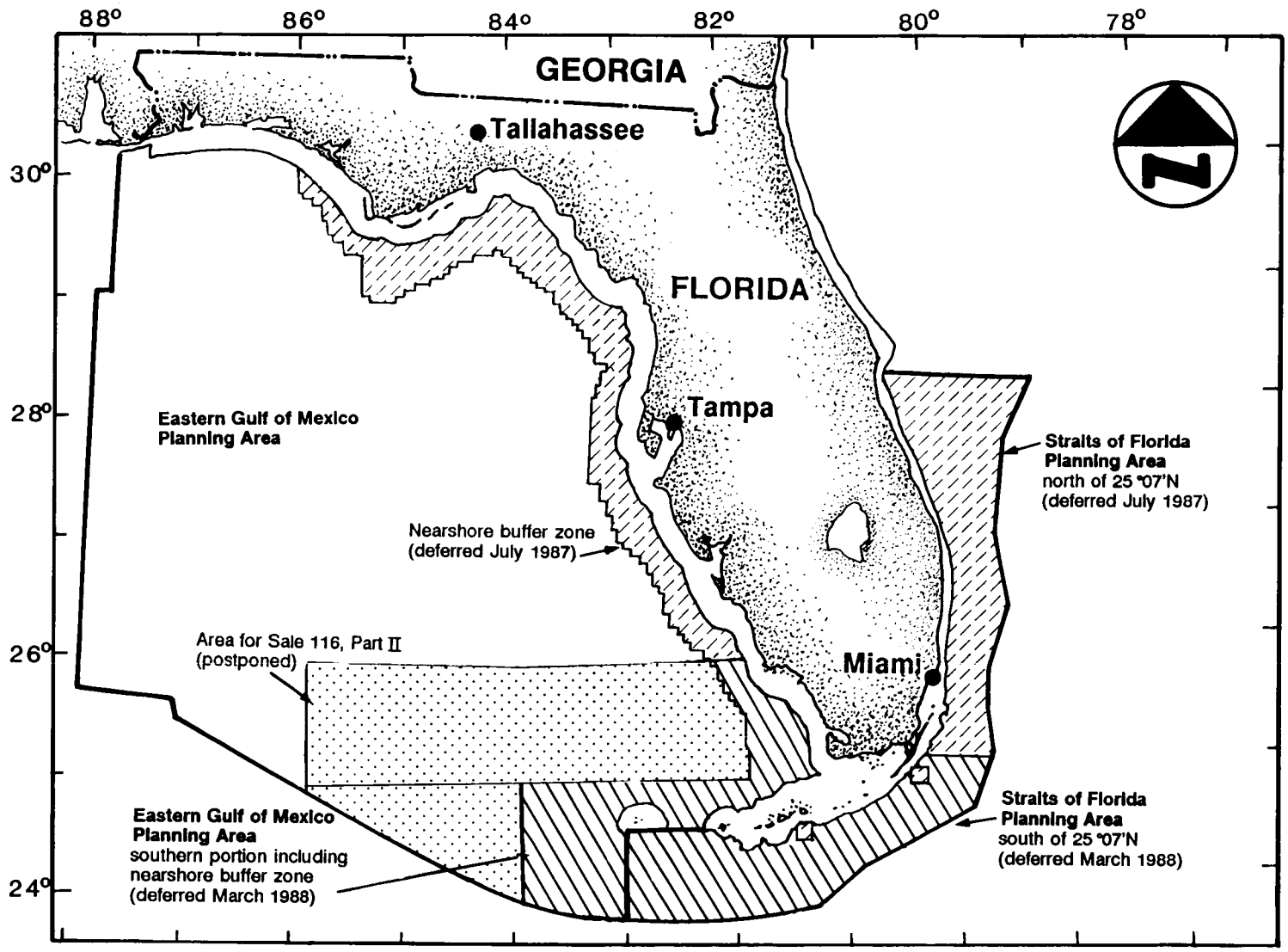

Figure 12.3. Leasing status of Straits of Florida and Eastern Gulf of Mexico Planning Areas.

Three task forces have recently studied environmental issues related to leasing and drilling off South Florida. Two Federal-State task forces were formed in June 1988 to study drilling effects and oil spill risks in the Pulley Ridge and Howell Hook map areas. The task force reports were issued in late 1989 (State of Florida and MMS 1989a,b). Also, in February 1989, a Presidential task force was formed to examine environmental issues associated with leasing and drilling off California and Florida. The Presidential task force asked the National Research Council (NRC) to evaluate the adequacy of environmental information for OCS leasing decisions (NRC 1989a). A second NRC panel evaluated hydrocarbon resource estimates for California and Florida (NRC 1989b). The Presidential task force delivered its report to the President in January 1990, but the report has not been released publicly (as of May 1990), and no decisions on South Florida leasing have been announced.

In both 1988 and 1989, Congress passed a one-year moratorium on leasing and drilling south of 26°N. Under the most recent moratorium, neither Sale 116, Part II nor the exploratory drilling proposed by two Pulley Ridge leaseholders could occur until October 1990.

The preceding discussion indicates that the future of leasing and drilling in the Pulley Ridge and Howell Hook map areas is uncertain. The outcome of this controversy will undoubtedly affect future leasing and drilling in the study area. The State's concerns about the protection of the Everglades, the Florida Keys, and Florida Bay are at the heart of its objections to drilling in Pulley Ridge and Howell Hook. Also, if drilling were to occur in Pulley Ridge or Howell Hook and oil or gas were discovered, this could create additional pressure to open adjacent areas for leasing. Alternatively, if drilling in those areas were to be unsuccessful, industry interest would probably turn elsewhere.

Possible Future Leasing in the Study Area

In the 5-Year Program issued in July 1987, the MMS proposed to lease that portion of the Straits of Florida Planning Area south of 25°07'N (**Figure 12.3**) (MMS 1987a). However, in response to opposition from the State of Florida, the Secretary of the Interior deleted the proposed Straits of Florida sale from the 5-Year Program in March 1988 (State of Florida, Office of the Governor 1988). The MMS had already stated that the northern part of the Straits of Florida Planning Area, as well as the Key Largo and Looe Key National Marine Sanctuaries, would be deferred if a lease sale were held.

Under the 5-Year Program issued in July 1987, those portions of the Dry Tortugas, Key West, and Miami map areas that are within the Eastern Gulf of Mexico Planning Area could have been included in two sales scheduled for 1988 and 1991. These areas were deferred from leasing in March 1988 under the agreement between the Secretary of the Interior and the State of Florida (State of Florida, Office of the Governor 1988).

Petroleum Potential

Geological models indicate that the offshore portion of the South Florida Basin has the potential for commercial accumulations of oil and gas (Attilio and Blake 1983; Amato et al. 1986; Faulkner and Applegate 1986; Montgomery 1987). Key stratigraphic units that have considerable reservoir potential include the Dollar Bay Formation, the Sunniland Formation, the Brown Dolomite zone in the Lehigh Acres Formation, and the Pumpkin Bay Formation (Faulkner and Applegate 1986; Applegate 1987) (see **Chapter 2**). True hydrocarbon potential is not known because few exploratory wells have been drilled in the offshore portion of the Basin (Montgomery 1987). Several wells drilled in the Florida Keys area had shows of oil (**Table 12.1**), and two wells drilled in the vicinity of the Marquesas Keys in 1959 and 1960 could have been low-volume oil producers (Applegate and Lloyd 1985, Appendix II).

The depocenter of the South Florida Basin is located on the Southwest Florida shelf northwest of the Florida Keys (Faulkner and Applegate 1986). Therefore, within the study area, it would appear that the resource potential and the probability of discovering commercial hydrocarbons are greater in the Eastern Gulf of Mexico Planning Area than in the Straits of Florida Planning Area. This is reflected in the statistics cited below and summarized in **Table 12.2.**

The U.S. Geological Survey (USGS) and MMS (1989) have estimated the total amount of undiscovered, economically recoverable hydrocarbons in the Straits of Florida Planning Area as 350 million barrels[2] of oil (range: 180 to 680 million barrels), and 0.44 trillion cubic feet of natural gas (range: 0.21 to 0.79 trillion cubic feet). These estimates are termed conditional because they hinge on the condition that at least one prospect contains economically recoverable hydrocarbons. That probability is currently estimated as 0.18 (USGS and MMS 1989).

No resource estimates are available for the portion of the Eastern Gulf of Mexico Planning Area that is within the current study area. However, the MMS recently issued resource estimates for the area south of 26°N proposed to be offered in Sale 116, Part II (MMS 1989a). The estimates are 610 million barrels of oil (range: 270 to 1,060 million barrels) and 0.11 trillion cubic feet of natural gas (range: 0.04 to 0.16 trillion cubic feet). The marginal probability of commercial hydrocarbons for the area south of 26°N is estimated to be >0.99 (rounded to 1.00). According to the NRC (1989b), methods used by the MMS to estimate resource potential for South Florida are valid. Independent estimates by Faulkner and Applegate (1986) indicate a range from 36 to 992 million barrels of oil for the Pulley Ridge area of the South Florida Basin. In recent hearings held by the Presidential task force, Unocal Corporation estimated that the South Florida Basin could contain more than 2.5 billion barrels of oil and 25 trillion cubic feet of natural gas (Schanck 1989).

Table 12.2. Resource estimates for the Straits of Florida Planning Area and the southern portion of the Eastern Gulf of Mexico Planning Area.

Location	Oil (millions of barrels)*	Gas (trillions of cubic feet)*	Marginal Probability of Commercial Hydrocarbons	Reference
Straits of Florida Planning Area	350 (180-680)	0.44 (0.21-0.79)	0.18	U.S. Geological Survey and Minerals Management Service (1989)
Eastern Gulf of Mexico Planning Area south of 26°N	610 (270-1,060)	0.11 (0.04-0.16)	1.00	Minerals Management Service (1989c)†
Pulley Ridge map area	36-992	–	–	Faulkner and Applegate (1986)
South Florida Basin	2,500	25	–	Schanck (1989)

* 1 barrel = 42 U.S. gallons = about 160 L. 1 cubic foot = 0.028 cubic meters.
† July 1989 estimate.

[2]Barrels are the customary unit used by the MMS to report oil resources, as well as spill volumes (1 barrel = 42 U.S. gallons, or about 160 L). Gas volumes are customarily reported in trillions of cubic feet (1 cubic foot = 0.028 cubic meters).

To put these figures in perspective, total U.S. production of crude oil in 1988 was approximately 8 million barrels/day, with Federal offshore production accounting for about 11% of the total (Energy Information Administration 1989). In addition, some 5 million barrels/day were imported. The mean estimated reserves for the Straits of Florida Planning Area equate to about 27 days of total U.S. oil consumption at the 1988 rate. The July 1989 MMS estimates for the Eastern Gulf of Mexico Planning Area south of 26° N equate to 47 days, and the UNOCAL estimates for the South Florida Basin equate to 192 days. The South Florida Basin by itself is not likely to be a major, new source of oil and gas, but it could be important as one of many contributors to the Nation's energy supply.[3]

It is important to keep in mind the tentative nature of these reserve estimates and to view them in the proper context. Offshore oil and gas exploration is an economically risky business, especially in a frontier area with no existing infrastructure. There is no assurance that economically recoverable volumes of oil and gas exist in the offshore South Florida Basin. The mean reserves estimated by the MMS for the Straits of Florida Planning Area may appear too low to generate much industry interest because of the low potential return on investment. However, companies that want to drill in a frontier area could be hoping to discover significant new reserves that might be considerably greater than those estimated by the MMS. In response to a 1986 questionnaire distributed by the MMS, the industry ranked the Straits of Florida Planning Area 20th out of 26 U.S. Planning Areas (MMS 1987b, Table 13.3). This ranking agrees closely with the ranking of the Planning Area on the basis of "risked" mean hydrocarbon potential (estimated conditional resources multiplied by the probability of commercially recoverable hydrocarbons; MMS 1987b, Appendix F, Table 6). However, in comments concerning the proposed 5-Year Program, seven oil companies favored a lease sale in the southern Straits of Florida Planning Area (MMS 1987a, Appendix B).

Exploration and Development Assumptions

The MMS projected the following level of exploration and development to result from a Straits of Florida lease sale (MMS 1987a, Appendix K):

Exploration/delineation wells	9
Development/production wells	13
Platforms	1
Pipelines to shore (oil)	0
Pipelines to shore (gas)	1

The mode of transport for crude oil from the offshore South Florida region cannot be determined until the amount of recoverable reserves is known and judgments are made as to the environmentally preferable and technically and economically feasible options (MMS 1987a, p. IV.A-20). However, crude oil from frontier areas with little or no existing infrastructure (e.g., Straits of Florida and Southwest Florida shelf) probably would be transported by tankers rather than pipelines. The tankers probably would transport crude oil to refineries in the northern Gulf of Mexico or the Mid-Atlantic region.

[3]Another way to evaluate the significance of the potential resources is to analyze benefits and costs to the State of Florida (see **Chapter 16**).

The MMS also estimated that one new onshore support base and one gas processing plant would be required, and that there would be one gas pipeline landfall in the area (MMS 1987a, Appendix K). Prospective locations for these facilities were not cited (see discussion later in this chapter). The MMS estimated that no heliports, refineries, marine terminals, pipe storage and coating yards, or platform fabrication yards would need to be constructed in the area, because existing facilities in Florida or elsewhere in the Gulf of Mexico would be adequate.

These estimates must be considered preliminary because they are tied to the tentative resource estimates for the Straits of Florida Planning Area published in 1987. Since then, the USGS and MMS (1989) have issued revised estimates of resource potential for the Straits of Florida Planning Area (reflected in **Table 12.2**). Mean estimates of oil resources tripled, whereas mean estimates of gas resources decreased by a factor of 2.5. Therefore, the level of exploration and development activities resulting from a lease sale may not be the same as listed above. Also, if economically recoverable volumes of oil or gas were not found, then there might be only a few exploration wells drilled. Alternatively, if substantial quantities of oil and gas were discovered, a much higher level of offshore and onshore activity might be expected on the initial leases and those acquired in subsequent sales, should they occur.

OVERVIEW OF OFFSHORE OIL AND GAS OPERATIONS

Offshore oil and gas operations can be grouped into four phases: Evaluation, Exploration, Development and Production, and Post-Production. Activities and potential environmental effects during each phase are discussed below.

Evaluation

During the evaluation phase, lease blocks are surveyed with a variety of equipment to evaluate hydrocarbon potential, identify prospective drill sites, map shallow drilling hazards, locate objects of archeological significance, and document epibenthic communities. Procedures for these surveys are regulated by the MMS.

Some geological and geophysical surveys are conducted prior to leasing, to provide information on deep geologic structure and hydrocarbon potential. These operations require a permit or notice from the MMS (MMS 1989b).

The MMS requires data from a shallow hazards survey for all proposed wells. In the eastern Gulf of Mexico, a remote sensing survey and an evaluation of the potential for historic and prehistoric artifacts is required for blocks in depths $\leq$45 m. In addition, all eastern Gulf of Mexico leases in water depths $\leq$100 m contain a "live bottom"[4] stipulation requiring a photographic survey of the seafloor and epibiota (MMS 1987c).

During shallow hazards surveys, geological and geophysical data are collected with fathometers, side-scan sonars, sparkers, subbottom profilers, and sometimes bottom sampling equipment (e.g., corers or grabs) (MMS 1984). If the lease is in water $\leq$45 m deep, additional data are collected with a magnetometer during the shallow hazards survey. The data must be evaluated by an archeologist and a geophysicist to determine whether archeological artifacts may be present.

[4]The MMS (1987c) defines live bottom as "seagrass communities; or those areas which contain biological assemblages consisting of such sessile invertebrates as sea fans, sea whips, hydroids, anemones, ascidians, sponges, bryozoans, or corals living upon and attached to naturally occurring hard or rocky formations with rough, broken, or smooth topography; or areas whose lithotope favors the accumulation of turtles, fishes, and other fauna."

In the Eastern Gulf of Mexico Planning Area in water depths $\leq$100 m, a photographic survey (live bottom survey) is conducted, generally after the shallow hazards survey is completed. Photographic coverage of the seafloor is necessary because geophysical instrumentation is often not able to detect dense growths of sessile epifauna (Continental Shelf Associates, Inc. 1987a). During these surveys, a towed camera sled or remotely operated vehicle is used to obtain photographs of the benthos. Dredge samples are collected if dense epifaunal growth is observed.

Numerous geologic hazards surveys and photographic documentation surveys have been conducted for Federal lease blocks off Southwest Florida (Charlotte Harbor and Pulley Ridge map areas) during the 1980s. Survey vessels have generally operated out of Tampa/St. Petersburg and Key West. To date, no environmental concerns have been raised about these activities off the Florida coast.

Geophysical surveys, at least on a small scale, do not pose much of an environmental hazard. However, there is some concern that noise produced by seismic equipment such as air guns and sparkers may temporarily disturb or harm marine mammals, sea turtles, and fish (MMS 1984). The use of explosives, which have the greatest potential for damaging or killing animals, is tightly controlled by the MMS and is permitted in only a small percentage of geophysical surveys (MMS 1984).

There has been considerable MMS-sponsored research on the subject of noise effects on migrating whales in Alaska and California (Gales 1982; Malme et al. 1985, 1989; also see review in MMS 1987b, Appendix I). Noise from seismic operations can result in avoidance reactions, but the detection distance varies depending on the species and environmental conditions. The MMS is currently sponsoring a synthesis of the effects of noise on marine mammals. A final report is due in the summer of 1990 (J. Wilson, pers. comm. 1990, MMS, Herndon, VA).

In California, some fishermen contend that geophysical surveys make it more difficult to catch fish (MMS 1988b). Preliminary studies have been conducted by Greeneridge Sciences, Inc. (1985), Malme et al. (1986), and Pearson et al. (1987). The MMS is currently conducting a study of the effects of geophysical survey sounds on California commercial fisheries (MMS 1988b).

Other concerns in relation to geological and photographic evaluation surveys include the potential for vessel collisions with endangered marine mammals and sea turtles, and possible space-use conflicts with commercial fishing activities such as shrimp trawling (MMS 1984).

Exploration

During the exploration phase, one or more wells are drilled to evaluate hydrocarbon potential. Depending on the success of initial drilling efforts, additional wells may be drilled to delineate hydrocarbon deposits and identify the most favorable locations for production drilling.

Three types of mobile drilling rigs are used to drill exploratory wells: jack-up rigs, semi-submersible rigs, and drillships (Exxon Corporation 1980). Jack-up rigs, which are generally used in water depths <100 m, are towed by tugboats to the drill site, where the legs are jacked down to rest on the bottom. This type of drilling rig could probably be used throughout most of the study area. Semi-submersible rigs, which can be used in somewhat deeper water (generally <800 m), are typically self-propelled; once on site, they are held in place by large, radially positioned anchors. Drillships are self-propelled

vessels that are held in place by anchors or dynamically positioned using thrusters. Drillships would be necessary for deeper waters of the Straits of Florida.

Exploratory drilling can affect the marine environment in a number of ways, but the effects are generally localized within a few hundred meters of a drill site. Installation and removal of mobile drilling rigs results in mechanical damage to the seafloor and benthic organisms at the drill site--either through anchoring or placement of jack-up legs. During the few months that a drilling rig is in place, it provides attachment surfaces for biofouling species (barnacles, hydroids, etc.) and attracts fish. Operational discharges (drilling fluids, cuttings) temporarily degrade water quality near the drill site and may bury or smother benthic organisms (see **Chapter 13**). Engines on board the drilling rig, support vessels, and helicopters produce noise and air emissions. Support vessels may collide with marine mammals or turtles during transit between the shore base and the drill site. Debris from the rig may clutter the bottom. Small oil spills may occur during fuel transfer operations, and there is a small chance of a blowout or other accident resulting in a large oil spill.

The joint Florida-MMS Drilling Impact Assessment Task Force recently evaluated potential environmental effects of exploratory drilling offshore Southwest Florida (State of Florida and MMS 1989a). The task force members identified oil spills, drilling fluid and cuttings discharges, and rig emplacement as the factors potentially producing the most severe environmental effects. They concluded that a large oil spill was unlikely during exploratory drilling, but if one did occur and oil reached the coast, coral reefs, mangroves, and seagrasses could be severely affected. The task force also concluded that seagrasses, coral reefs, and certain live bottom communities were susceptible to damage from rig emplacement and drilling fluid and cuttings discharges.

Observations of previous exploratory drill sites in the eastern Gulf of Mexico and Florida Keys provide some indication of potential effects of future drilling. One exploratory well site in the Florida Big Bend area was the subject of an elaborate monitoring program during 1985 to 1986 (Continental Shelf Associates, Inc. 1988a). Another well site on the Southwest Florida shelf was observed visually before and after exploratory drilling in 1986 (Continental Shelf Associates, Inc. 1987b). The exploratory wells that were drilled in the Marquesas Keys area between 1959 and 1962 were not observed before or during drilling, but one site was visited many years later by Smith and Hunt (1979), and all were surveyed recently by Shinn et al. (1989).

Most other programs to monitor exploratory drilling have not dealt with tropical or subtropical habitats (EG&G Environmental Consultants 1982; Maciolek-Blake et al. 1985). Coral reefs at the Flower Garden Banks off the Texas coast have been monitored several times during exploratory and production drilling, but environmental restrictions and the location of the reefs on top of high-relief banks prevented exposure of the corals to mechanical damage or drilling effluents (see Phillips and James 1988, Appendix A, for a review).

Florida Big Bend Monitoring Program

Continental Shelf Associates, Inc. (1988a) monitored exploratory drilling in Gainesville Block 707, located on the continental shelf in the Florida Big Bend area. A single exploratory well was drilled in a water depth of about 20 m, from June through November 1985. A monitoring program was set up to evaluate the effect of drilling effluents on the seagrass *Halophila decipiens*. Within one month after drilling began, all seagrass within a 300 m radius of the drill site was killed. There was some evidence for a reduction in seagrass growth out to 3,700 m from the drill site, although only one reference site was available for comparison. Seagrass mortality and growth reductions

were attributed to smothering near the drill site, as well as chronic turbidity resulting from nearly continuous, low-volume drilling fluid and cuttings discharges released into an area of weak currents (Continental Shelf Associates, Inc. 1988a).

The results of the seagrass monitoring program were confounded by the effects of Hurricane *Elena*, which passed almost directly over the site about halfway through the drilling program. The hurricane destroyed all seagrass over a broad expanse of the continental shelf in the Florida Big Bend area (Continental Shelf Associates, Inc. 1987c), making it impossible to determine the long-term effects of drilling on seagrass. Seagrass was observed at the site during the following summer and during November of 1987. During the latter survey, sampling revealed that drilling fluids were still present in bottom sediments, but there was no relation between drilling fluid concentration and seagrass density (Continental Shelf Associates, Inc. 1988a). It was not possible to determine whether seagrass would have recovered normally if the hurricane had not occurred.

The species of seagrass monitored in Gainesville Block 707 is also found offshore within the current study area (Continental Shelf Associates, Inc. 1989). Because *Halophila* is not a major "bed former" like *Thalassia*, the ecological significance of the seagrass mortality (other than the direct loss of production) is not clear. The results of this monitoring program suggest that other seagrasses in shallow water (e.g., *Thalassia* in Hawk Channel inshore of the Florida Reef Tract) would be sensitive to reductions in water clarity resulting from drilling discharges. However, because of the different species present and the natural turbidity that occasionally occurs in nearshore waters, it is not a simple matter to extrapolate from the results of the Gainesville Block 707 monitoring program to potential effects on seagrass beds in South Florida coastal waters.

Charlotte Harbor Block 622 Monitoring Program

In 1986, Continental Shelf Associates, Inc. (1987b) monitored exploratory drilling in water depths of 70 to 80 m, about 160 km (87 nmi) off Sanibel Island. The bottom habitat consisted of coralline algal rubble, with a sparse sessile epifauna and a variety of other algae present. Video and still cameras were towed over the drill site before and after drilling. No obvious effects of drilling were seen, other than the presence of a thin film of sediment (possibly drilling fluids) on the coralline algae.

The Charlotte Harbor Block 622 well site was revisited in 1988 by Shinn et al. (1989). They noted the presence of numerous pieces of debris, including a length of pipe, a chair, plastic buckets, and used welding rods. Grout from the conductor casing had produced a mound approximately 1 m high and 10 to 15 m in diameter, resulting in burial of the benthic community around the well site. No widespread effects that might be attributable to drilling discharges were noted.

Marquesas Well Site Surveys

Shinn et al. (1989) visited six former exploratory well sites near the Marquesas Keys. The Marquesas wells were drilled between 1959 and 1962, before environmental restrictions on OCS drilling came into effect. At one well site, the "footprints" of a 14-legged jack-up rig were still visible 28 years after drilling. The legs had been placed on coral bottom, resulting in 4.5-m diameter circles of barren sand. At another well site, large amounts of pea gravel had been used to level the bottom, and about 100 cement bags had been discarded over the well site, resulting in altered bottom topography and local smothering of the biota. Scattered pieces of debris at most sites

functioned as artificial reefs, providing surface area for attachment of corals and algae and attracting reef fish.

Shinn et al. (1989) concluded that the only observable environmental effects of exploratory drilling were attributable to physical disruption of benthic habitats. The most severe damage occurred at the older sites, where drilling practices were used that would not be allowed today. The accumulation of debris observed at the recent drill sites need not have occurred, and the technology exists to clean up these sites after drilling is completed.

Although Shinn et al. (1989) attributed all environmental effects to physical/ mechanical disruption of the seafloor, it is possible that other effects occurred but the communities recovered in the intervening years. Also, observations at the Marquesas sites suggest that coral communities there are subject to natural disturbance on a time scale of 20 to 30 years or less; drilling effects might be different if a more mature coral community were disturbed (P. Dustan, pers. comm. 1990, College of Charleston).

Development and Production

During the development and production phase, platforms are installed to extract oil and gas. The extracted oil is transported by pipeline or tanker to onshore facilities. In the northern Gulf of Mexico, most of the oil is transported by pipeline because of the well-developed onshore facilities (Risotto and Collins 1986). There is no onshore infrastructure for oil and gas processing in South Florida, and oil produced here would probably be transported by tankers. Gas might be transported to shore via a pipeline (MMS 1987a, p. IV.A-20), but the landfall could not be in the study area for reasons discussed later in this chapter.

Many of the environmental concerns about development and production activities are the same as those associated with exploration, but the magnitude and duration of the effects may be greater (Neff et al. 1987). Installation of a production platform results in mechanical damage to the seafloor and benthic organisms. The presence of a semi-permanent, submerged structure leads to the development of a dense biofouling community and a platform reef-fish assemblage (Gallaway and Lewbel 1982; Boland et al. 1983; Reggio 1989). Deposition of cuttings and fallout of biological debris from the platform can attract benthic scavengers (fishes and mobile invertebrates) to the site, resulting in a halo effect on surrounding benthic communities (Wolfson et al. 1979). Increased populations of benthic predators, scouring of sediments by bottom currents, and deposition of contaminants from effluent discharges can result in a depauperate benthic infauna under the platform (Harper et al. 1981). The degree of benthic scouring and the magnitude and persistence of cuttings deposits vary depending on water depth and the hydrographic regime.

Drilling fluid and cuttings discharges also occur during the development and production phase. With 20 to 30 wells typically drilled from a single platform, there is a greater potential for cumulative effects of these discharges on the benthos. Once the wells are producing, drilling fluid and cuttings discharges cease, but discharges of produced water (formation water extracted with the oil) begin. Environmental aspects of these discharges are discussed in **Chapter 13.**

There is still considerable debate about the long-term, chronic, and cumulative effects of offshore development and production. There have been three major environmental studies of production fields in the Gulf of Mexico: the Offshore Ecology Investigation (Ward et al. 1979), the Central Gulf Platform Study (Bedinger 1981), and the Buccaneer Gas and Oil Field Study (Middleditch 1981). Unfortunately, all three

studies had problems with experimental design, execution, and confounding environmental variables that make it difficult to reach definitive conclusions about environmental effects (Carney 1987). The applicability of these studies to South Florida is uncertain because the environments are so different from those of the northern Gulf of Mexico (e.g., the Mississippi River discharge is not a factor in South Florida).

There is a greater chance of an oil spill during development and production operations than during exploratory drilling. The probability of a blowout (or other accident) resulting in a spill of crude oil is still low. However, there is a chance of a spill during transfer operations and during transport of the oil to refineries. Oil spills are discussed in a separate section below.

Post-Production

The production life of an offshore platform is generally 20 to 25 years (NRC 1985b). If leasing and development were to occur off South Florida, the problem of how to remove and dispose of these structures would eventually arise.

Currently, there are over 3,600 offshore oil and gas platforms and related structures on the northern Gulf of Mexico OCS, and 73 platforms were removed in 1988 (MMS 1989c). In the past, most platforms have been removed by using bulk explosive charges to sever platform legs. The shock waves from these explosions are propagated through the surrounding waters and can kill or injure fishes, sea turtles, and dolphins (Klima et al. 1988). Alternative removal methods are available, including the use of shaped charges, mechanical cutters, or underwater arc cutters (MMS 1987d).

There is increasing interest in using obsolete platforms as artificial reefs (NRC 1985b; Reggio 1989). Florida has a vigorous artificial reef program, under which several former oil platforms have been sunk off Broward County (Shinn and Wicklund 1989). There probably would be no shortage of sites for disposal of old platforms in Florida.

SPECIAL ENVIRONMENTAL CONCERNS IN SOUTH FLORIDA

This section discusses potential environmental effects of offshore oil and gas drilling that are of particular concern in South Florida.

Oil Spills

A large oil spill is a rare, but potentially catastrophic event. Biological effects of spilled oil are discussed in **Chapters 14** and **15**, and social costs are evaluated in **Chapter 16.** This discussion is intended to provide the context for those chapters.

A brief discussion of terminology is in order. I will refer to spills of <1,000 barrels as "small;" those of ≥1,000 barrels as "large;" and those of ≥100,000 barrels as "very large." Small spills may not be reported as accurately, have lower potential for environmental damage, and are not as appropriate for trajectory analysis as large and very large spills (Anderson and LaBelle 1988; MMS 1989b).[5]

[5]The terminology is arbitrary and not universal. The MMS sometimes uses 10,000 barrels as the cutoff for a large spill. The Petroleum Industry Response Organization Steering Committee (1990) refers to spills <1,200 barrels as "small;" those between 1,200 and 25,000 barrels as "medium;" and those ≥25,000 barrels as "catastrophic."

To put these figures in perspective, **Table 12.3** lists some historical spills, including two large spills (*Garbis* and *Howard Star*) in South Florida. From a practical standpoint, spills larger than 25,000 barrels in the open sea (or 40,000 barrels in coastal waters) are beyond the capability of any single, existing U.S. spill cleanup organization (Petroleum Industry Response Organization [PIRO] Steering Committee 1990). The PIRO Steering Committee (1990) recently used a figure of 216,000 barrels as a target for developing new spill response capability (discussed later in this chapter).

Oil spills are one of several sources of petroleum input to the oceans, including (1) transportation; (2) municipal and industrial wastes and runoff; (3) atmosphere; (4) natural marine seeps; and (5) offshore production (NRC 1985a). Transportation (shipping and related activities) accounts for 45.3% of the total input. This contribution is followed closely by municipal and industrial wastes and runoff (36.3%). Input from the atmosphere amounts to 9.4%, and input from natural marine seeps accounts for 7.6%. The last category, offshore production, which includes input from exploration and production activities and from pipeline transmission, accounts for 1.4% of the total input into the marine environment.

Two potential sources of large oil spills in South Florida are discussed below: tanker traffic and offshore drilling/production.

Existing Oil Spill Risk from Tanker Traffic

The risk of a large oil spill already exists in the study area in the form of tanker traffic that passes through the Straits of Florida. Tankers travelling from the Middle East, West Africa, the North Sea, Mexico, Venezuela, and other sources converge on the Straits enroute to ports in the Gulf of Mexico, the U.S. Mid-Atlantic coast, and other destinations (Reinburg 1984).

Table 12.3. Sizes of some historical oil spills.

Spill Name	Date	Source	Location	Volume (Barrels)*	Reference
Zoe Colocotroni	1973	tanker	Puerto Rico	37,000	Gilfillan et al. 1981
Garbis	1975	tanker	Florida Keys	1,500 to 3,000	Chan 1977
Howard Star	1978	tanker	Tampa Bay	1,000	Getter et al. 1980
Ixtoc-I†	1979	blowout	Mexico	3 to 5 million	Boehm 1982
Funiwa V	1981	blowout	Nigeria	200,000	Baker 1981
Bahia las Minas	1986	tank failure	Panama	50,000	Jackson et al. 1989
Exxon Valdez	1989	tanker	Alaska	240,000	National Response Team 1989

* 1 barrel = 42 U.S gallons = about 160 L.
† Largest oil spill in history.

In 1976, the U.S. Coast Guard (USCG) estimated that tankers carrying approximately 3 billion barrels of oil passed through the Straits of Florida within 8 to 40 km (4 to 22 nmi) of the coast (Research Planning Institute 1983). The South Florida Regional Planning Council (SFRPC) (1984) estimated that there were over 5,500 transits[6] of the Straits of Florida in 1979, with over 1.2 billion barrels of crude and refined oil passing through the area. Reinburg (1984) estimated approximately 1,000 transits by cargo-laden tankers in 1984, based on 12 days of observations by the USCG. Reinburg (1984) did not state the total volume of oil carried, but it can be estimated from his data at about 500 million barrels/year. There is a discrepancy between these figures, and it is clear from all sources that accurate estimates of the number of tankers and the volume of oil passing through the Straits are not easily derived. The USCG does not routinely monitor the level of vessel traffic in the heavily traveled Straits (D. Whitten, pers. comm. 1989, USCG, Miami).

Four locations within the Straits of Florida and vicinity have been identified as crossing/merging hazard areas with a potential for oil spill incidents (**Figure 12.4**) (SFRPC 1984):

1. 21 km (11 nmi) south southeast of West Palm Beach. This is an area of crossing of north-south traffic with westbound traffic to and from North Africa through the Providence Channel.

2. 19 km (10 nmi) east southeast of Ft. Lauderdale. There is a hazard here because of north-south traffic intersecting with tankers transporting refined and crude oil into and out of Port Everglades.

3. 21 km (11 nmi) south southeast of Miami. In this area, 33,000 annual Miami Harbor trips merge with the large volume of through traffic.

4. 23 km (12 nmi) south of the Dry Tortugas. This is a converging area for most traffic entering the Straits of Florida from the west.

The oil spill risk due to tanker traffic in the Straits of Florida has been estimated by the SFRPC (1984). The projected number of "spill incidents" was 0.310 per year, based on the 1979 level of tanker traffic. However, this figure is not very useful because spills of all sizes are lumped together. Also, the source of the spill probabilities is not stated explicitly.

The MMS has estimated the spill rate for tankers at sea as 0.9 spills of 1,000 barrels or more per billion barrels transported (Anderson and LaBelle 1988). For spills of 10,000 barrels or more, the rate is 0.55 per billion barrels transported (**Table 12.4**).[7] If the estimate of 1.2 billion barrels/year transported through the Straits of Florida is correct (SFRPC 1984), then the estimated mean annual number of spills of 1,000 barrels or more is 1.08, and the estimated mean annual number of spills of 10,000 barrels or more is 0.66. However, the proportion of this risk that applies to the Straits of Florida transit is not known. The length of tanker trips varies greatly depending on the source and destination. Based on the major tanker routes shown by Reinburg (1984) and the relative distances involved, I will assume that 1 to 10% of the total spills from tankers that pass through the Straits of Florida will occur while the tankers are within the study area. The estimated mean spill rates in the study area

[6]Each transit actually consists of two passages through the Straits: one while the vessel is laden with cargo, the other while the vessel is loaded with ballast.

[7]The rates for spills of $\geq$1,000 barrels and $\geq$10,000 barrels are not additive.

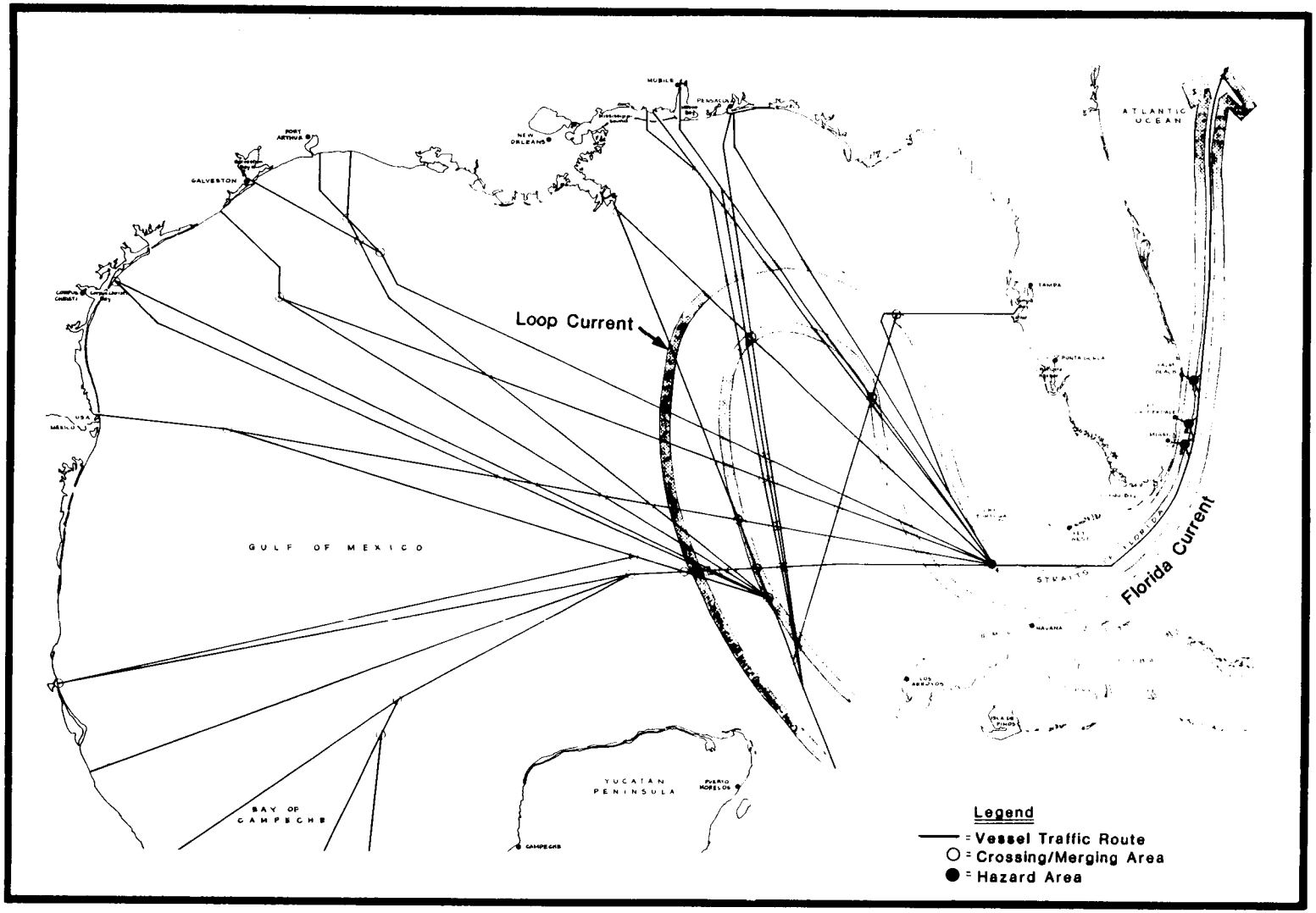

Figure 12.4. Vessel traffic routes and hazard areas in the Straits of Florida (From: South Florida Regional Planning Council 1984b).

Table 12.4. Oil spill and blowout statistics.

SPILL RATES*

Source	Number of Spills per Billion Barrels Handled	
	≥1,000 barrels	≥10,000 barrels
Platforms	0.60	0.24
Pipelines	0.67	0.17
Tankers (at sea)	0.90	0.55
Tankers (in port)	0.40	0.16

MEAN AND MEDIAN SPILL SIZES (barrels)†

	Platforms	Pipelines	Worldwide Tankers
Mean	18,000	25,000	106,000
Median	7,000	6,000	15,000

BLOWOUTS§

Time period: 1971 through 1985
Location: U.S. outer continental shelf
Total number of new wells drilled: 15,334

Phase of Operations	Number of Blowouts	Total Barrels Spilled
Drilling		
Exploration	33	0
Development	28	10
Non-drilling		
Production	7	566
Workover	18	264
Completion	12	0
TOTAL	98	840

* Platform, pipeline, and tanker spill rates are from Anderson and LaBelle (1988). Platform and pipeline spill rates were calculated by analyzing the U.S. outer continental shelf statistical record from 1964 through 1987 and are based on the most recent 60% or more of the record. Tanker spill rates were calculated directly from the worldwide tanker data base for 1974 through 1985.

† Mean and median sizes of platform and pipeline spills were calculated by the Minerals Management Service (MMS) Branch of Environmental Modeling from the U.S. outer continental shelf statistical record, 1964 through 1988 (spills ≥1,000 barrels listed by Harris and Thurston 1989, Table 65). Mean and median sizes of tanker spills were calculated by the MMS Branch of Environmental Modeling from the worldwide tanker data base, 1974 through 1985, based on (spills ≥1,000 barrels, in port and at sea).

§ Blowout statistics are from MMS 1987b, Appendix Q.

would be 0.01 to 0.1 spills of 1,000 barrels or more and 0.007 to 0.07 spills of 10,000 barrels or more per year. Thus, spills of 1,000 barrels or more might be estimated to occur every 10 to 100 years. The last reported large spill occurred in 1975 when the tanker *Garbis* discharged 1,500 to 3,000 barrels in the Florida Keys (Chan 1977).

The calculations above do not take into account the possibility of large spills from vessels other than tankers. During one three-week period in October and November 1989, three freighters grounded on South Florida reefs: one near the Dry Tortugas and two in the Key Largo National Marine Sanctuary (National Marine Sanctuary Program 1989). All three ships carried thousands of gallons of fuel oil, but fortunately, none of their tanks ruptured.

The risk of a large spill, or even a very large spill on the order of the *Exxon Valdez* incident, exists in the study area due to tanker traffic in the Straits of Florida. The exact magnitude of the risk is not known. On the other hand, the most common type of spill is of a much smaller volume and may often go unreported and unnoticed. High concentrations of pelagic tar to the west of the Dry Tortugas and south of the Florida Keys have been attributed to tanker discharges (see **Chapter 3**). There are numerous anecdotal reports of spilled oil in the area (Robertson and Robertson, 1982; C. Getter, pers. comm. 1989, Riedel Environmental Services, Inc.; W. Jaap, pers. comm. 1989, Florida Department of Natural Resources).

Potential Oil Spill Risk from Drilling and Production

Offshore drilling, production, and subsequent transportation of oil also carry a risk of oil spillage. Most of the spills that occur during drilling and production are small diesel spills during transfer operations (Cotton 1986). There is a low probability of a large spill resulting from a well blowout, fire, tank rupture, or other accident, although several such spills have occurred during the last 20 years (**Table 12.5**). The greatest risk is during transportation of oil by tankers. The risk of crude oil spillage exists only if oil is present in the study area.

Historical data concerning the safety performance of the offshore industry are available from the U.S. Department of the Interior, which has maintained a computerized events file since 1971 (Cotton 1986; MMS 1987b, Appendix Q). Data from prior to 1971 are not complete because no comprehensive file was kept. These data can be used to estimate the probability of oil spills during drilling and production. A necessary assumption is that the safety of future drilling operations will be governed by the same set of factors that determined the probability of past spills.

Diesel Spills. Small fuel spills that occur during transfer operations are the most frequent type of spill during OCS drilling and production. Most diesel spills during exploratory drilling have occurred during fuel transfer from the supply vessel to the drilling platform and from collisions involving support vessels. From 1976 through 1985, there were approximately 3,620 new wells in Federal waters of the Gulf of Mexico (Cotton 1986; U. Cotton, pers. comm. 1987, MMS, Reston, VA). During this period, there were 72 reported diesel spills (a total of 4,736 barrels) that were associated with exploratory drilling (Cotton 1986). Nearly all of the spills occurred as a result of an accident during transfer operations from the supply vessel to the drilling platform. Sixty-one of these instances involved spills of <50 barrels, whereas in 11 cases spills were >50 barrels. The largest diesel spill (and the only one >1,000 barrels) occurred in 1979 when an anchor-handling boat collided with a drilling platform and released 1,500 barrels. Based on these data, for a given well, there is a 2.0% overall probability of a diesel spill; a 1.7% probability of a diesel spill <50 barrels; and a 0.3% probability of a diesel spill >50 barrels.

Table 12.5. Oil spills of 1,000 barrels or more on the U.S. outer continental shelf between 1964 and 1989 (From: Harris and Thurston 1989).

Date	Location	Size (barrels)*	Cause
Platforms			
1964	Louisiana	2,559	Freighter struck platform
1964	Louisiana	5,180	Hurricane
1964	Louisiana	5,100	Hurricane
1964	Louisiana	1,589	Hurricane
1965	Louisiana	1,688	Blowout
1969	California	77,000†	Blowout
1969	Louisiana	2,500	Collision, blowout
1970	Louisiana	30,000	Fire
1970	Louisiana	53,000	Blowout, fire
1973	Louisiana	9,935	Storage tank rupture
1973	Louisiana	7,000	Storage barge sank
1979	Louisiana	1,500	Collision with rig (diesel)
1980	Texas	1,456	Pump failure, tank overflow
Pipelines			
1967	Louisiana	160,638	Anchor damage
1968	Louisiana	6,000	Anchor damage
1969	Louisiana	7,532	Anchor damage
1973	Louisiana	5,000	Internal corrosion
1974	Louisiana	19,833	Anchor damage
1974	Louisiana	3,500	Hurricane
1976	Louisiana	4,000	Shrimp trawl damage
1981	Louisiana	5,100	Anchor damage
1988	Texas	14,944	Anchor damage

* 1 barrel = 42 U.S. gallons = about 160 L.
† Estimates vary from 10,000 to 77,000 barrels.

Blowouts. A blowout is a sudden, often violent release of hydrocarbons to the marine environment caused by a loss of well control. A blowout can cause death, personal injury, and property damage. In addition, if crude oil or condensate are involved, an oil spill can result. Depending on the environmental conditions (mainly wind and currents) and the adequacy of contingency plans, such an oil spill could reach the coast or nearshore habitats (e.g., seagrass beds, corals reefs) and result in severe environmental damage and considerable cleanup expenses.

Drilling blowouts are rare events--especially on the U.S. OCS, where stringent blowout prevention regulations are in effect. From 1971 through 1985, over 15,000 new wells were drilled on the U.S. OCS, with only 61 drilling blowouts (**Table 12.4**) (MMS 1987b, Appendix Q). None of the 33 blowouts during exploratory drilling from 1971 through 1985 resulted in a spill of crude oil or condensate. A blowout during development drilling in 1984 resulted in spillage of 10 barrels.

Blowouts can also occur during production, workover, or well completion. Between 1971 and 1985, 37 non-drilling blowouts occurred on the U.S. OCS (MMS 1987b, Appendix Q). The total volume of oil spilled from non-drilling blowouts was 830 barrels, with the largest single spills being 450 barrels (1971) and 200 barrels (1974).

The largest spill caused by a blowout in U.S. waters was the 1969 Santa Barbara Channel spill. Estimates of the amount spilled range from 10,000 to 77,000 barrels (Harris and Thurston 1989, Table 65). A blowout off the Louisiana coast in 1971 resulted in spillage of 53,000 barrels (**Table 12.5**).

The largest oil spill in history resulted from an exploratory well blowout in the Bay of Campeche, Mexico. The *Ixtoc-I* blowout occurred in June 1979 and was not capped until March of the following year. During that time, an estimated 3 to 5 million barrels of oil were released into the Gulf of Mexico (Boehm 1982).

Different geological formations have different potential for abnormal pressure that might cause a blowout. According to industry sources and a recent Florida-MMS task force report, the available geological information from South Florida indicates there is little likelihood of encountering abnormal pressures during offshore drilling (Schanck 1989; State of Florida and MMS 1989b).

Transportation. Once oil is extracted, it must be transported from the platform(s) to onshore facilities for processing. In the northern Gulf of Mexico, most oil is transported to shore by an immense network of pipelines (Risotto and Collins 1986). At least initially, anticipated production off South Florida would not justify the expense of installing pipelines, which might be difficult to obtain permits for in any case. Oil produced off South Florida probably would be transported by tankers to facilities in the northern Gulf of Mexico or the U.S. Mid-Atlantic coast (MMS 1987a).

A recent update of oil spill statistics by Anderson and LaBelle (1988) indicates that the rate of spillage by tankers has remained constant since last evaluated in 1983. Based on data from 1974 through 1985, the rate (in spills of 1,000 barrels or greater per billion barrels transported) is 0.9 for tankers at sea and 0.4 for tankers in port (**Table 12.4**). Transportation by U.S. OCS pipelines is safer than tanker transport (0.67 large spills per billion barrels). However, several large pipeline spills have occurred in the Gulf of Mexico over the last 20 years, mostly due to anchor damage (**Table 12.5**).

Existing vs. Potential Oil Spill Risk

One consideration in regard to offshore drilling in South Florida is whether this activity would produce an increase in the risk of a large oil spill. This is not a simple issue.

Proponents of offshore drilling argue that extraction of domestic reserves from the OCS will reduce the risk of oil spills from tankers carrying imported oil (Johnson 1989). Although this ought to be true in general, it is not necessarily so for the Straits of Florida area. First, tanker traffic through the Straits carries oil to and from a number of sources, both domestic and foreign (Reinburg 1984). It is not clear that a slight increase in domestic production would cause a corresponding decrease in tanker traffic through the Straits. Second, oil produced in the study area probably would be transported by tankers. If a certain volume of imported oil passing through the Straits were displaced by production from the study area, the spill risk would actually increase. The total spill rate per billion barrels produced would be the sum of the platform spill rate (0.6) and some fraction of the tanker spill rate $(0.9)^{8}$, whereas with tankers alone, only the fraction of the tanker spill rate would apply. There is more risk from producing and transporting a given volume of oil than in transporting the same volume through the study area.

How does the existing risk from tanker traffic compare with the potential risk from drilling and production in the study area? The answer depends on how much oil is present. If there are no appreciable quantities of oil, then there is no direct risk of a large crude oil spill from drilling. (There might be an indirect risk if drilling rigs and support vessels created a hazard to navigation in the Straits of Florida). If crude oil is present, the estimated mean number of spills will depend on the volume.

[8]The fraction would represent the proportion of the total risk during the average tanker trip that is incurred during passage through the Straits of Florida (assumed in this chapter to be 1 to 10%).

The volume of oil passing through the Straits of Florida in tankers has been estimated at about 1.2 billion barrels/year (SFRPC 1984). Calculations above suggest a mean estimated number of spills (1,000 barrels or more) of about 0.01 to 0.1 per year based on this volume of tanker traffic, with the assumption that 1 to 10% of the total spill risk occurs while a tanker is in the study area. The maximum amount of crude oil estimated to exist in the Straits of Florida area is 680 million barrels (**Table 12.2**). If this amount were produced over a 20-year period, the annual production would be 34 million barrels/year, or about 3% of the annual volume transported by tanker[9]. Assuming (1) that the platform spill rate is 0.6 per billion barrels produced, (2) that the tanker spill rate is 0.9 for the crude oil produced in the study area (Anderson and LaBelle 1988), and (3) that 1 to 10% of the tanker spills occur in the study area, the estimated mean number of spills from production in the Straits of Florida would be 0.021 to 0.023 per year. This is at the lower end of the range estimated above for tanker spills. These calculations and similar ones for spills $\geq$10,000 barrels are summarized below:

	Estimated Mean Annual Number of Spills	
	$\geq$1,000 barrels	$\geq$10,000 barrels
Tanker traffic in Straits	0.010 to 0.10	0.007 to 0.070
OCS production & transportation	0.021 to 0.023	0.008 to 0.010

These calculations suggest two conclusions. First, the existing risk of a large oil spill from tanker traffic is probably much greater than the risk of a spill from drilling and production in the Straits of Florida, unless huge new oil reserves are discovered. Second, drilling and production probably would increase the risk of a large spill. The magnitude of the increase would depend on the volume of oil discovered. Because of the many assumptions and uncertainties in the calculations presented above, the probabilities provide only a general idea of the magnitude of oil spill risk.

A complicating factor in comparing the existing spill risk from tankers vs. the hypothetical risk from OCS drilling and production is the difference in mean and median spill sizes for tankers vs. OCS platforms. Specifically, tanker spills tend to be much larger than platform spills (**Table 12.4**).

Fate of Spilled Oil

The location and magnitude of an oil spill and the fate of the spilled oil will determine whether nearshore and coastal environments are affected. Even a very large spill might have no apparent environmental effects if the oil were rapidly carried away into the open ocean (e.g., the *Argo Merchant* spill; NRC 1985a). Alternatively, a small spill in the wrong location under quiescent conditions might have severe local effects on coastal and nearshore communities (see **Chapter 15**).

The most likely locations for a tanker accident are on the Straits of Florida side of the Florida Keys. The SFRPC (1984) has identified four hazard areas where one might expect the highest risk of an accident (**Figure 12.4**). Vessel grounding is also a possibility, as exemplified by the grounding of the freighter *Wellwood* on Molasses Reef in 1984 (Hudson and Diaz 1989) and three recent groundings on reefs in the Florida Keys and Dry Tortugas (National Marine Sanctuary Program 1989).

[9]This estimate is high. A production rate of 34 million barrels/year is about four times the total 1988 onshore oil production in Florida (D. Curry, pers. comm. 1989, Florida Bureau of Geology). For comparison, the highest annual crude oil production of all Federal leases offshore California has been about 31 million barrels (La Liberte and Harris 1987).

OCS drilling and production in the Straits of Florida Planning Area might increase the risk of a spill there by creating hazards to navigation (e.g., offshore structures and crossing vessel traffic). Drilling and production in the Eastern Gulf of Mexico Planning Area just north of the Dry Tortugas and Florida Keys would introduce additional risk of spillage into the Florida Bay side of the Keys. Oil spilled in this area could be transported toward the Southwest Florida coast, Florida Bay, the Dry Tortugas, and the north side of the Florida Keys; or it could reach the Loop Current and be transported around to the Florida Keys, Reef Tract, and Southeast Florida (State of Florida and MMS 1989b).

Two important aspects of the fate of spilled oil are transport and transformations. Transport refers to the physical movement (advection and spreading) of oil due to wind and ocean currents. Transformations include a variety of physical, chemical, and biological changes, such as evaporation, emulsification, sedimentation, and biodegradation (NRC 1985a).

Transformation. Hydrocarbon transformation processes are discussed in **Chapter 3.** Other pertinent references include NRC (1985a), Bartha and Atlas (1987), Boehm (1987), and Payne et al. (1987).

The State of Florida and MMS (1989b) discussed transformations of a hypothetical 1,000-barrel spill consisting of Sunniland crude oil (the oil found onshore in South Florida). Evaporation is expected to be the dominant process initially. Within one day, about one-third of the total mass would be expected to evaporate. After three days, about one-half of the spilled volume would remain, and emulsification would be forming mousse (water-in-oil emulsion). After 10 days, the oil would be more weathered, with more mousse forming small tar balls (1 to 10 mm in diameter). Tar balls would be expected to be in patches of weathered oil at the surface, and would be trailed by a thin, iridescent sheen. Sedimentation would continue to deplete the oil slick at this stage. After 30 days, only weathered oil would remain; biodegradation and sedimentation would continue to reduce spill mass.

Transport. Some information on the transport of spilled oil off Southwest Florida is available through drift bottle studies (Williams et al. 1977) and trajectory modeling (Continental Shelf Associates, Inc. 1987d; State of Florida and MMS 1989b). Some trajectories ("a statistically representative number") have also been run for launch points in the Straits of Florida, as part of an assessment of spill risk from tankering (MMS 1989b, 1990). These studies indicate that oil spilled in or near the study area could reach the Florida Keys, Dry Tortugas, or mainland Florida coast within a few hours to several days.

The most elaborate, realistic, and useful modeling efforts are those reported by the State of Florida and MMS (1989b). A model developed by the MMS was used to evaluate the transport of spilled from four hypothetical launch points on the Southwest Florida shelf just north of the study area (Pulley Ridge and Howell Hook map areas). According to the NRC (1989a), the specific numerical results of the trajectory modeling conducted by the State of Florida and MMS (1989b) can be considered a good first-order approximation (NRC 1989a) of oil transport off Southwest Florida. Nevertheless, the *qualitative* findings about the fate of spilled oil are the most important outcome of the modeling effort.

The State of Florida and MMS (1989b) simulations show that the Loop Current and the Florida Current provide a powerful mechanism for exposing much of the study area to spilled oil. Specifically, the results show that oil spilled on the Southwest Florida shelf could be entrained in the Loop Current within a few days and transported rapidly

around to the Florida Keys and Southeast Florida. The results are in accord with observations of high concentrations of tar on Southeast Florida beaches, which have been attributed to transport of Gulf of Mexico tanker discharges by the Loop Current and the Florida Current (see **Chapter 3**). In some cases simulated, oil spilled north of the Dry Tortugas was entrained in the Loop Current, carried around to the Straits of Florida, then blown back through the Florida Keys to hit Florida Bay or the Southwest Florida coast. The simulated spills entrained in the Loop Current reached these latter areas faster by the indirect route than by direct transport toward the mainland coast. Thus, time for oil to reach shore is not strictly a function of the proximity of the spill site to shore.

Oil carried by the Loop Current and Florida Current could impinge upon coastal areas through eddy or meander formation, or through winds blowing across the axis of the main current. As an example, oil spilled from the *Garbis* on 18 July 1975 in the Straits of Florida, at a point 42 km (23 nmi) south-southwest of the Marquesas Keys, oiled shorelines from Boca Chica Key to Little Pine Key beginning on 21 July 1975 (Chan 1977). Easterly winds blowing across the main axis of the Florida Current drove the slick ashore and spread it across a 56-km (30-nmi) stretch of shoreline.

Oil entrained in the Loop Current could also be transported out of the study area without hitting the coast. For example, a 1970 spill from an unknown vessel completely missed the Florida Keys, despite the formation of a 120 km (65 nmi) long slick seen at John Pennekamp Coral Reef State Park (Smithsonian Institution 1971). Also, an oil spill entrained in these major currents would be subject to shear because of the large velocity gradient; consequently, a slick could become elongated and broken into many long streamers, and mousse formation could be enhanced (State of Florida and MMS 1989b).

Contingency Planning

Large oil spills are rare events, but they do occur. Contingency planning is necessary to minimize the chance of oil reaching sensitive shorelines (e.g., mangrove forests) and nearshore habitats (e.g., coral reefs and shallow, subtidal seagrass beds).

On a National level, the Clean Water Act of 1977 provides for the development of a National Oil and Hazardous Substance Pollution Contingency Plan (commonly referred to as the National Contingency Plan) to deal with oil spills and other pollution incidents [Florida Department of Natural Resources (FDNR) 1988]. Under the National Contingency Plan, the USCG provides on-scene coordinators (OSC) to direct the response to oil spills. The OSC is responsible for notifying the spiller, directing and monitoring cleanup efforts, and providing advice to the spiller as necessary (MMS 1988c). If the spiller cannot be identified or fails to respond adequately, the USCG has working agreements with local cleanup companies throughout the Gulf of Mexico; the Atlantic Area Strike Team, located in Mobile, AL, is available to respond to large or very large spills (MMS 1988c). A Regional Response Team consisting of various State and Federal agency representatives provides advice to the OSC as requested. A National Response Team, consisting of representatives from 14 Federal agencies, is available to provide additional resources and to assist in major policy decisions.

The National Contingency Plan is supplemented and complemented by Regional Response Plans and State Response Plans. Florida is covered by the Atlanta Coastal Region IV Contingency Plan, which also covers Alabama, Georgia, Mississippi, North Carolina, and South Carolina (FDNR 1988). The USCG is responsible for the coastal aspects of the Regional Contingency Plan. In Florida, the FDNR is the lead agency in dealing with coastal pollution incidents.

The offshore petroleum industry also develops contingency plans for oil spills. The MMS requires operators to submit oil spill contingency plans before receiving permits for conducting offshore operations. These plans are reviewed annually (MMS 1988c). Companies drilling offshore Florida have had to develop additional contingency plans to satisfy the State of Florida (Continental Shelf Associates, Inc. 1987d). Also, in the Gulf of Mexico, a group of oil companies has formed the Marine Industry Group, which serves to identify the location of cleanup equipment, identify sensitive environments, and develop spill prevention and containment measures (MMS 1988c).

Contingency plans on several different levels are undergoing reevaluation following the March 1989 *Exxon Valdez* spill in Prince William Sound, Alaska. A report by the National Response Team (National Response Team 1989) points out that contingency plans for the Alaska spill site were inadequate. The USCG has been directed to evaluate the adequacy of existing plans to deal with large spills (D. Whitten, pers. comm. 1989). Florida Governor Martinez recently ordered State officials to update Florida's contingency plans to deal with such a massive spill, and created a State Spill Response Task Force that recently issued a draft report outlining specific measures to reduce spill risk (Spill Response Task Force 1990). Most of the task force recommendations are concerned with vessel operations in and near Florida ports.

The oil and gas industry has also reacted to recent events by forming the Petroleum Industry Response Organization (PIRO), which plans to establish five regional centers to handle spills that exceed the capacity of existing spill response cooperatives (American Petroleum Institute 1989; PIRO Steering Committee 1990). None of the existing cooperatives can handle an open ocean spill larger than 25,000 barrels, whereas each PIRO regional center would have the capacity to respond to a 216,000 barrel spill.

If leasing does occur, companies planning to drill in the study area will have to develop oil spill contingency plans to satisfy the MMS and the State of Florida. As part of the planning process, trajectory modeling can be used to determine how much time there would be to respond before oil reached the shoreline or other features of interest.[10] Results reported by the State of Florida and MMS (1989b) for launch points on the Southwest Florida shelf just north of the study area indicate that oil could reach Florida Bay, the Dry Tortugas, the Florida Keys, or the Reef Tract in one to three days. The minimum time to reach these points did not strictly reflect distance; oil reached the Reef Tract faster from launch points further offshore because the oil was transported with the Loop Current.

The risk of a large or very large spill already exists in the study area because of the large number of tankers and other large vessels passing through the Straits of Florida. The adequacy of existing contingency plans to deal with such a spill is unknown. This is a critical issue, regardless of whether drilling and production ever occur in the study area.

To allow more time to respond in the event of a tanker spill, Florida's Governor recently reached an agreement with 15 oil companies to keep their tankers at least 18 km (10 nmi) offshore when transiting the Straits of Florida (State of Florida, Office

[10]Trajectory modeling for contingency planning purposes is not the same as the modeling conducted by the MMS for each lease sale. MMS trajectory modeling focuses narrowly on the probabilities that a spill from a given point will reach various shoreline segments. These statistical probabilities are virtually meaningless if only one or a few spills are expected. Because the trajectory of an individual spill cannot be predicted in advance with confidence, the main goal of modeling for contingency planning is to estimate the minimum time in which a spill could reach a particular target. This can be estimated by simulating trajectories under "worst case" assumptions (Continental Shelf Associates, Inc. 1987d), or by simulating many trajectories and identifying those in which oil reaches shore in the shortest time (State of Florida and MMS 1989b).

of the Governor 1990). At the request of the Governor and the President, the USCG will propose a similar avoidance zone in June 1990 to the International Maritime Organization. The proposal would apply to all American and foreign vessels carrying cargos of oil or hazardous material, and all other vessels of 500 metric tons or more.

Drilling Near Biologically Sensitive Areas

Drilling activities have the potential to damage or degrade the environment around drilling rigs and platforms. Except in the event of a well blowout resulting in a large oil spill, the environmental effects of drilling can be expected to be localized within a few hundred meters of a drill site (NRC 1983; Neff et al. 1987). The main concern is that drilling not occur where the biota are sensitive to mechanical disturbance or effluent discharges.

The study area contains the most dense concentration of environmentally sensitive habitats anywhere on the U.S. OCS. Habitats found within Federal waters (i.e., potentially open to leasing) include coral reefs, nearshore seagrass (*Thalassia*) beds, offshore live bottom habitats, and deepwater (*Halophila*) seagrass meadows.

Most of the major reefs in the Florida Reef Tract are located in Federal waters potentially open to leasing and drilling. Under the proposed Straits of Florida lease sale described in the 5-Year Program (MMS 1987a), leasing would be deferred in the two National Marine Sanctuaries (Key Largo and Looe Key) that are within the study area. However, leasing would still be allowed up to the border of these marine sanctuaries and in other portions of the Reef Tract, including the deep reef that occurs seaward of the major bank reefs (see **Chapter 5**).

Surveys of old exploratory well sites in the Marquesas Keys by Shinn et al. (1989) indicate that the major lasting effects of drilling were attributable to physical/mechanical disruption of the seafloor. Modern restrictions on drilling practices probably would have prevented the kinds of damage to corals and other biota that were observed by Shinn et al. (1989). However, other, less-lasting environmental effects might have occurred (Shinn et al. visited the sites over 25 years after the wells were drilled). Also, the effects might be different in areas of more mature coral growth (P. Dustan, pers. comm. 1990). Potential effects of drilling on coral reefs are discussed in more detail in **Chapter 13**.

The major *Thalassia* seagrass beds are located in State waters in Florida Bay (see **Chapter 4**). However, extensive *Thalassia* beds also occur in Hawk Channel, the lagoon behind the Florida Reef Tract. Some of this area is in Federal waters (Marszalek 1982). Also, offshore seagrass meadows dominated by *Halophila decipiens* occur extensively on the Southwest Florida shelf (see **Chapter 5**). A monitoring program in the Florida Big Bend area (discussed above) has shown that these seagrasses are sensitive to drilling discharges (Continental Shelf Associates, Inc. 1988a) (see also **Chapter 13**). Little is known of the productivity and ecological relationships within these offshore seagrass meadows. Therefore, it is difficult to judge the significance of environmental damage that might occur as a result of drilling discharges in the area.

Low-relief hard bottom areas colonized by sponges, stony corals, octocorals, and other reef biota are widely distributed on the Southwest Florida shelf and occur offshore of the Reef Tract on the Straits of Florida shelf (see **Chapter 5**). Live bottom areas are considered important because they attract reef fish (Cummins et al. 1962; Struhsaker 1969; Darcy and Gutherz 1984). The occurrence of live bottom is so patchy and unpredictable on the Southwest Florida shelf that site-specific visual surveys are required

for each lease block. There has been no quantitative monitoring of the effects of drilling on these benthic communities off West Florida.

Biologically sensitive areas are protected by the MMS in two main ways: through lease sale deferrals and lease stipulations. Another way in which sensitive environments and biota can be protected is through the regulation of drilling discharges by the U.S. Environmental Protection Agency (EPA). These measures are discussed later in this chapter under Regulatory Considerations.

Hazards to Navigation

The Straits of Florida is a major shipping corridor. Installation of temporary or semi-permanent structures (rigs or platforms) and addition of crossing vessel traffic in this area would probably increase the risk of marine traffic accidents. Because of the large number of tankers and other large vessels traveling through the Straits, this is a serious concern that should be evaluated carefully.

According to a 1976 study by the USCG, vessels travelling either way through the Straits of Florida follow well-defined routes. East- or northbound traffic tends to travel 15 to 24 km (8 to 13 nmi) offshore of the reef-line navigational aids, converging on the Florida Current in the vicinity of Alligator Reef Light. Southbound or westbound traffic tends to travel inshore of the Florida Current, about 2.5 to 5 km (1.3 to 2.6 nmi) offshore of the reef-line navigational aids (USCG 1976). However, recently 15 oil companies agreed to keep their tankers at least 18 km (10 nmi) offshore during passage through the Straits of Florida, in order to reduce the risk of vessel groundings and oil spills (State of Florida, Office of the Governor 1990).

The four hazard areas pinpointed by the SFRPC (1984) in the Straits of Florida (**Figure 12.4**) all involve crossing or merging vessel traffic. One would not expect offshore operations to result in nearly the volume of traffic entering and exiting ports such as Port Everglades, Miami, and West Palm Beach. However, some additional risk of an accident could be involved.

Responsibility for regulating marine navigation on the OCS is shared by the USCG and the U.S. Army Corps of Engineers. The USCG designates fairways and traffic separation schemes. The authority of the USCG to regulate vessel movement in the Straits of Florida is limited because much of the traffic is in international waters (D. Whitten, pers. comm. 1989). There is no formal fairway or traffic separation scheme in place, but there is a *de facto* separation based on water current patterns, as noted above (SFRPC 1984).

Placement of structures such as drilling rigs and platforms on the OCS requires a permit from the U.S. Army Corps of Engineers (MMS 1988c). Structures are not allowed in designated fairways. Lighting requirements are specified by the USCG.

Vessel Traffic

Boat and ship traffic is associated with all phases of offshore oil and gas operations. Vessel traffic could contribute to destruction of nearshore seagrass habitats and result in collisions with endangered marine mammals and sea turtles--depending on the location of the onshore service base. Because of the limited scope of operations anticipated by the MMS (1987a) and the low likelihood of a service base being located in the study area (see below), OCS vessel traffic should not present a major environmental problem.

The risk of vessel collisions with marine mammals and turtles would seem to be low in the open ocean. However, it is reasonable to be concerned about the potential for boat collisions with manatees if a shore base were located within the critical range of the species. The current population of manatees is estimated at 1,200; over 100 mortalities have been reported each year for the past few years, with about one-third of those attributable to boat traffic in Florida waterways (see **Chapter 8**). All exploratory drilling to date on the Southwest Florida shelf has used Port Manatee (in Tampa Bay) as a shore base. UNOCAL, which is one of the two Pulley Ridge leaseholders currently awaiting the outcome of CZM consistency appeals to the Department of Commerce, has proposed to use Ft. Myers (Continental Shelf Associates, Inc. 1988b). Choice of Ft. Myers required a jeopardy opinion from the U.S. Fish and Wildlife Service (USFWS) because vessel traffic to and from the onshore base would have to pass through the critical habitat of the manatee.

Voss (1988) noted that the large volume of boat traffic nearshore in the Florida Keys (e.g., in Hawk Channel) contributes to the destruction of seagrass habitat, both directly and indirectly through stirring up of bottom sediments. It is unlikely that a shore base for OCS drilling would be located in the Florida Keys (see below). If the vessel traffic remains offshore, the risk of damage to nearshore habitats should be minimal.

Dumping of Trash and Debris

The dumping of trash and debris in marine waters from boats, ships, and offshore platforms is becoming a serious problem (O'Hara 1988). Plastic sheeting, plastic bags, monofilament fishing line, and other such refuse have been implicated in the deaths of marine mammals, sea turtles, and birds through ingestion and entanglement (Bunn 1988). Trash can foul and smother corals, gorgonians, and other reef organisms (P. Dustan, pers. comm. 1989, College of Charleston). Also, vast quantities of marine debris ultimately wind up on the beaches. Aside from the obvious negative effect on the enjoyment of the beaches, this material costs money to clean up, and some can present a health hazard (e.g., medical waste).

The offshore oil and gas industry is one of many contributors to the marine debris problem in the Gulf of Mexico (Kewley 1988). In Texas, which has extensive offshore oil and gas operations, surveys of Mustang Island beaches have identified debris from 34 countries (Amos 1988). Sources of debris include ships, rigs, platforms, recreational vessels, shrimp boats, and supply boats. Florida, which does not have extensive offshore oil and gas operations, ranked second to Texas in a recent nationwide cleanup effort, with over 190 tons of debris collected from 1,475 km (795 nmi) of beaches (Clark 1989).

A recent U.S. law prohibits dumping of plastics from ships at sea and restricts disposal of other garbage and debris (MMS 1989b). The Marine Pollution Research and Control Act of 1987 implements Annex V of the International Convention for the Prevention of Pollution from Ships. The USCG is responsible for enforcing provisions of the new law, most of which went into effect at the end of 1988. Designation of the Gulf of Mexico as a "Special Area" under Annex V is being proposed by the EPA to the Marine Environmental Protection Committee of the International Maritime Organization. This designation would prohibit all non-plastic waste disposal in the area, with the exception of food waste discharged no less than 22 km (12 nmi) from land (*Florida Coastal Update*, February 1990).

Although laws and strict enforcement can reduce at-sea disposal of trash and debris, education and awareness are the real keys to solving this problem. In 1986, the MMS issued a Notice to Lessees (NTL 86-11), advising oil companies in the Gulf of Mexico

that offshore oil and gas operations were contributing to a chronic problem of marine debris (MMS 1988c). The Offshore Operators Committee has produced a videotape program to educate offshore personnel, and encourages them to participate in beach cleanup activities (Kewley 1988). In the last few years, there has been a reduction in oil- and gas-related debris on Louisiana and Texas beaches, perhaps due in part to the industry's educational efforts (Amos 1988; Kewley 1988).

A post-drilling survey of an exploratory well site on the Southwest Florida shelf revealed the presence of hundreds of welding rods and other metal debris (Shinn et al. 1989). The well was drilled in 1986. The presence of metal debris on the bottom indicates that rig personnel were not conscientious about littering the environment. If further drilling is allowed off South Florida, education and/or additional regulation of rig personnel is needed to minimize the debris problem.

Siting of Onshore Facilities

In its description of a proposed Straits of Florida lease sale, the MMS estimated that one new onshore support base and one gas processing plant would be required, and that there would be one gas pipeline landfall in the area (MMS 1987a, Appendix K). Prospective locations for these facilities were not cited. The MMS estimated that no heliports, refineries, marine terminals, pipe storage and coating yards, or platform fabrication yards would need to be constructed in the area, because existing facilities in Florida or elsewhere in the Gulf of Mexico would be adequate.

The SFRPC (1984) evaluated potential locations for service bases for offshore oil and gas operations. Only one possibly suitable location for a service base was identified in Monroe County, on Boca Chica Key just north of Key West. Subsequently, Monroe County adopted a comprehensive plan that changed the land use designation of this site to commercial fishing (MMS 1987c). Also, because of the limited water supply and nearly universal opposition to offshore drilling in the Florida Keys, it is very unlikely that any onshore facilities would be permitted there by local governments.

The nearest likely locations for onshore service bases are near Port Everglades (north of Miami) and Port Manatee (in Tampa Bay). Port Everglades is a major port that supports the second largest volume of tanker traffic in the U.S. Port Manatee has served as a support base for exploratory drilling on the Southwest Florida shelf. Closer to the study area, San Carlos Island near Ft. Myers is considered marginally suitable as a base for exploratory drilling (Southwest Florida Regional Planning Council 1983). UNOCAL has proposed to use that base to support exploratory drilling in Pulley Ridge (Continental Shelf Associates, Inc. 1988b). Mobil, the other leaseholder that has proposed to drill in Pulley Ridge, considered the Ft. Myers site to be unsuitable and proposed to use Port Manatee (Continental Shelf Associates, Inc. 1988c).

Lack of a nearby service base would be expensive and inconvenient for the oil companies, but would not preclude them from operating in the study area. However, because of the long travel time from a distant shore base, it would probably be necessary to station a dedicated response vessel at the drilling rig or platform to deal with minor oil spills. This approach was required by the MMS for POEs submitted by UNOCAL and Mobil for drilling in the Pulley Ridge area (Continental Shelf Associates, Inc. 1988b,c).

The SFRPC (1984) indicated that a possible location for a pipeline landfall in South Florida would be near Everglades City (Ten Thousand Islands area). A gas pipeline routed north from this location could hook into the Sunniland pipeline to Port Everglades (SFRPC 1984). From an environmental standpoint, the Ten Thousand

Islands area is not a good choice for a pipeline landfall because of the likely destruction of mangrove habitat. This point is moot now, because a Florida law passed in 1989 prohibits placement of oil and gas structures, including pipelines, in State waters south of 26° N on the Gulf coast or south of 27° N on the Atlantic coast (D. Tucker, pers. comm. 1989). Therefore, if there is a pipeline landfall, it would have to be outside the study area.

A gas processing plant removes impurities from raw gas and separates valuable gaseous hydrocarbons such as methane, butane, and propane from heavier components (SFRPC 1984). The plant must be located between a pipeline landfall and a commercial gas transmission line. The MMS (1987a) states that a gas processing plant may be needed as a result of a future lease sale in the Straits of Florida. However, the SFRPC (1984) indicates that construction of a gas processing plant in Florida is unlikely unless there is a very large find. Also, there should be no need for a gas processing plant if there is no gas pipeline landfall in the study area.

REGULATORY CONSIDERATIONS

If leasing does eventually occur in the study area, regulatory mechanisms exist that can limit, minimize, or avoid environmental damage from most routine OCS operations. Some have already been mentioned. For a comprehensive review of the regulatory framework, see a recent Environmental Impact Statement (e.g., MMS 1989b, 1990). Some relevant examples are cited below:

- Lease sale deferrals can be used to prevent specific areas (e.g., the Florida Reef Tract) from being exposed to drilling activities, or to preclude an OCS-related oil spill from occurring near the coast. Deferral of leasing near biologically sensitive areas has been standard practice off West Florida and elsewhere in the Gulf of Mexico (e.g., around the Flower Garden Banks and the Florida Middle Ground) (MMS 1987c). For three recent lease sales in the Eastern Gulf of Mexico Planning Area, the MMS established a nearshore buffer extending 37 to 56 km (20 to 30 nmi) seaward from the Florida Three League Line. The purpose of this buffer, established at the request of the State of Florida, was to protect sensitive nearshore habitats and to allow additional time to prevent an oil spill from reaching the coast (MMS 1987c).

- Lease stipulations can be used to ensure that benthic habitats and archeological resources in a given lease block are mapped and mitigation measures are taken to avoid damage. Leases in the recent Sale 116, Part I for the Eastern Gulf of Mexico Planning Area contained a live bottom stipulation, an archeological stipulation, and information to lessees about protection of the Florida manatee (MMS 1988d). The live bottom stipulation requires lessees to conduct site-specific photographic surveys of the benthic community in each lease block in water depths $\leq$100 m. If reef biota or seagrasses are found, the MMS has several options to protect the community, including relocation of the drill site, and onshore disposal of drilling discharges. Biological monitoring may also be required (MMS 1987c).

- The EPA regulates pollutant discharges from OCS facilities through the National Pollutant Discharge Elimination System (NPDES). The EPA can restrict or prohibit discharges near biologically sensitive areas such as coral reefs or seagrass beds. **Chapter 13** discusses regulation of drilling discharges.

- Under Section 7 of the Endangered Species Act, the MMS must consult with the USFWS and the National Marine Fisheries Service (NMFS) concerning OCS actions that might jeopardize Endangered and Threatened species or their critical habitat. For example, if a shore base were chosen within the critical habitat of the manatee (e.g., Ft. Myers), the USFWS would be required to render a jeopardy opinion before the activity could proceed.

- A Fishermen's Contingency Fund, administered by NMFS, has been established to compensate fishermen for gear loss and damage due to presence of OCS structures.

- The U.S. Army Corps of Engineers, in consultation with the USCG, must approve placement of structures such as rigs and platforms on the OCS. Approval would require an evaluation of potential hazards to navigation.

- The State of Florida has a State Implementation Plan for air quality, coupled with regulatory enforcement and monitoring programs that would apply to OCS lease blocks in the study area.

- Through the CZM review process, the State of Florida would have the opportunity to evaluate OCS activities that might affect the State's coastal zone. In the extreme case, the State could veto a proposed project (subject to appeal by the lessee to the Secretary of Commerce). The CZM review process also affords the State an opportunity to work with lessees to minimize or avoid environmental damage as a condition of CZM approval.

CONCLUSIONS

The South Florida Basin is a promising, frontier region for oil and gas exploration. Its hydrocarbon potential is unknown because few exploratory wells have been drilled in the geochemically mature offshore portions of the basin. The basin depocenter, which is the most favorable location for commercial hydrocarbons, is in the Pulley Ridge map area, adjacent to the portion of the study area within the Eastern Gulf of Mexico Planning Area. Therefore, in the study area, there is a greater likelihood of finding oil or gas in the Eastern Gulf of Mexico Planning Area than in the Straits of Florida Planning Area. If proposed exploratory drilling occurs in the Pulley Ridge map area, the hydrocarbon potential of the South Florida Basin will probably be much better known by the time leasing could occur in the study area.

Several environmental issues concerning drilling and production have been discussed in this chapter. These concerns cannot be evaluated fully, because resource potential, which determines the magnitude of OCS operations, is not accurately known. However, in general, there seems to be little risk of environmental damage from evaluation and exploratory operations. Most of the environmental effects of these activities are localized and temporary, and regulatory mechanisms exist that can limit, minimize, or avoid environmental damage. In contrast, environmental effects of large-scale development, which conceivably could occur in the event of a major find, are not as well known. Studies of production fields in the northern Gulf of Mexico have been flawed, and in any case the results are of uncertain value for predicting effects in South Florida.

Although large oil spills are rare events, they do occasionally occur during OCS operations. There is already a risk of a large spill from tankers passing through the Straits of Florida. This risk is not currently under the control of the Federal or State government, because the Straits is an international waterway. The recent, voluntary

agreement by some tanker owners (and possible future agreements involving others) to stay clear of the Florida Keys during passage through the Straits should help to reduce this risk. The estimated risk of a spill from OCS drilling and production operations (including transportation) is in the low end of the range estimated for existing tanker traffic. However, OCS drilling and production would probably increase the risk of a large spill, for two reasons: (1) these OCS activities would not necessarily result in a commensurate decrease in tanker traffic through the Straits; and (2) there is more risk associated with producing and transporting a given volume of oil (by tanker) than with transporting the same volume by tanker.

Adequate oil spill contingency plans, as well as equipment and personnel to execute them, are critical to protection of South Florida coastal habitats, whether or not offshore drilling is allowed. The adequacy of existing plans is currently under review by Federal and State governments, as well as industry.

No existing oil spill response measures can prevent oil from reaching oil-sensitive environments if a large or very large spill were to occur close to shore (or close to the Loop Current, which can rapidly transport oil to the Florida Keys and Reef Tract). Trajectory modeling of spills can be a useful tool to estimate the minimum time for oil to reach shore from various potential spill locations. This information could be used, for example, to develop buffer zones--i.e., areas where OCS activities or tanker traffic are prohibited because there would be insufficient time to respond to a large spill. The adequacy of existing physical oceanographic data for trajectory modeling is a critical issue that is being evaluated under a separate MMS contract (J. Wilson, pers. comm. 1990, MMS, Herndon, VA).

Accurate information is needed about the number of tankers and other large vessels passing through the Straits of Florida, in order to evaluate the existing risk of oil spills. The discussion of data sources by Reinburg (1984) makes it clear that tanker traffic cannot be calculated indirectly with confidence (e.g, by examining the volume entering or leaving various ports). Direct counts of tankers are preferable, but over a greater time period than the 12 days reported by Reinburg (1984).

Because of the large volume of tanker traffic through the Straits of Florida, potential hazards to navigation resulting from placement of OCS structures should be evaluated and taken into account in decisions about leasing in the Straits of Florida Planning Area.

REFERENCES CITED

Amato, R. V., W. E. Sweet, G. M. Edson, C. J. O'Hara, D. M. Clark, and G. Pickens. 1986. *Regional geology and petroleum potential of the Straits of Florida Planning Area*. U.S. Department of the Interior, Minerals Management Service. Unpubl. manuscript.

American Petroleum Institute. 1989. *The American Petroleum Institute task force report on oil spills*. Washington, DC.

Amos, A. F. 1988. Survey and findings of beach debris on Mustang Island, Texas. In *Proceedings, Eighth Annual Gulf of Mexico Information Transfer Meeting*, 53-55. OCS Study MMS 88-0035. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Anderson, C. M., and R. P. LaBelle. 1988. Update of occurrence rates for accidental oil spills on the U.S. outer continental shelf. In *Proceedings, Oceans '88*, 1673-1676. Washington, DC: IEEE.

Applegate, A. V. 1987. *The brown dolomite zone of the Lehigh Acres formation (Aptian) in the South Florida Basin--A potentially prolific producing horizon offshore*. Fla. Bur. Geol. Info. Circ. No. 104, Pt. II. Tallahassee.

Applegate, A. V., and J. M. Lloyd. 1985. *Summary of Florida petroleum production and exploration, onshore and offshore, through 1984*. Fla. Bur. Geol. Info. Circ. No. 101. Tallahassee.

Attilio, D. E., and B. Blake. 1983. Petroleum potential, exploration possibilities of S. Florida basin, Florida Keys. *Oil Gas J.*, 7 Nov. 1983:148-153.

Babcock, C. 1962. *Florida petroleum exploration, production, and prospects*. Fla. Geol. Surv. Spec. Publ. No. 9. Tallahassee.

Baker, J. M. 1981. The investigation of industry influences on tropical marine ecosystems. *Mar. Pollut. Bull.* 12:6-10.

Bartha, R., and R. M. Atlas. 1987. Transport and transformation of petroleum: Biological processes. In *The long-term effects of offshore oil and gas development*, ed. D. F. Boesch and N. N. Rabalais, 287-341. New York: Elsevier.

Bedinger, C. A., Jr., ed. 1981. *Ecological investigations of petroleum production platforms in the central Gulf of Mexico*. New Orleans: Bureau of Land Management.

Boehm, P. D. 1982. *Ixtoc oil spill assessment final report*. Report by ERCO/Energy Resources Company Inc. to the Bureau of Land Management, Washington, DC. NTIS Nos. PB82-197773, PB82-197779, and PB82-197781.

Boehm, P. D. 1987. Transport and transformation processes regarding hydrocarbon and metal pollutants in offshore sedimentary environments. In *The long-term effects of offshore oil and gas development*, ed. D. F. Boesch and N. N. Rabalais, 233-286. New York: Elsevier.

Boland, G. S., B. J. Gallaway, J. S. Baker, and G. S. Lewbel. 1983. *Ecological effects of energy development on reef fish of the Flower Garden Banks*. Galveston: National Marine Fisheries Service, Southeast Fisheries Center.

Bunn, A. R. 1988. NOAA's marine entanglement research program: Goals, products, information, and plans. In *Proceedings, Eighth Annual Gulf of Mexico Information Transfer Meeting*, 62-65. OCS Study MMS 88-0035. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Carney, R. S. 1987. A review of study designs for the detection of long-term environmental effects of offshore petroleum activities. In *Long-term environmental effects of offshore oil and gas development*, ed. D. F. Boesch and N. N. Rabalais, 651-696. New York: Elsevier.

Chan, E. I. 1977. Oil pollution and tropical littoral communities: Biological effect of the 1975 Florida Keys oil spill. In *Proceedings, 1977 Oil Spill Conference (Prevention, Behavior, Control, Cleanup)*, 539-542. Washington, DC: American Petroleum Institute.

Clark, J. 1989. Ocean pollution prompts nationwide effort. *Stuart News*, 6 September 1989, p. B4.

Continental Shelf Associates, Inc. 1987a. *Southwest Florida regional biological communities survey, Year 3 final report*. OCS Study MMS 86-0109. Metairie: U.S. Department of the Interior, Minerals Management Service.

Continental Shelf Associates, Inc. 1987b. *Monitoring study of a drillsite location in Charlotte Harbor Area Block 622*. Report for Shell Offshore Inc., New Orleans, LA.

Continental Shelf Associates, Inc. 1987c. *Assessment of hurricane damage in the Florida Big Bend seagrass beds*. OCS Study MMS 87-0001. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Continental Shelf Associates, Inc. 1987d. *Oil spill trajectory analysis and description of sensitive environments for Pulley Ridge lease area*. Report submitted to the Florida Petroleum Council OCS Ad Hoc Advisory Committee.

Continental Shelf Associates, Inc. 1988a. *Monitoring of drillsite A in the Gainesville Area Block 707*. Report to Sohio Petroleum Company, Houston, TX.

Continental Shelf Associates, Inc. 1988b. *Site-specific environmental report. Gulf of Mexico: Offshore Florida. Pulley Ridge Area Block 629 (OCS-G 6491), Block 630 (OCS-G 6492), Block 716 (OCS-G 6510), Block 760 (OCS-G 6518), and Block 761 (OCS-G 6519)*. Report to Union Exploration Partners, Ltd., Houma, LA.

Continental Shelf Associates, Inc. 1988c. *Site-specific environmental report. Gulf of Mexico: Offshore Florida. Pulley Ridge Area Block 799 (OCS-G 6520)*. Report to Mobil Exploration & Producing U.S. Inc., New Orleans, LA.

Continental Shelf Associates, Inc. 1989. *Southwest Florida nearshore benthic habitat study*. OCS Study MMS 89-0080. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Cotton, U. 1986. *Oil spills, 1976-85: Statistical report*. OCS Rep. MMS 86-0085. Washington, DC: U.S. Department of the Interior, Minerals Management Service.

Cummins, R., Jr., J. B. Rivers, and P. Struhsaker. 1962. Snapper trawling explorations along the southeastern coast of the United States. *Commer. Fish. Rev.* 24:1-7.

Darcy, G. H., and E. J. Gutherz. 1984. Abundance of demersal fishes on the West Florida shelf, January 1978. *Bull. Mar. Sci.* 34:81-105.

EG&G Environmental Consultants. 1982. *A study of environmental effects of exploratory drilling on the mid-Atlantic outer continental shelf: Final report of the Block 684 monitoring program*. Report to the Offshore Operators Committee, New Orleans, LA.

Energy Information Administration. 1989. *Petroleum supply annual 1988, Vol. 1*. DOE/EIA-034(88)/1. Washington, DC: U.S. Department of Energy.

Exxon Corporation. 1980. *The offshore search for oil and gas, fourth edition*. Exxon Background Series. New York.

Faulkner, B. M., and A. V. Applegate. 1986. Hydrocarbon exploration evaluation of the Pulley Ridge area, offshore South Florida Basin. *Trans. Gulf Coast Assoc. Geol. Soc.* 36:83-95.

Florida Coastal Update. 1990. February 1990 issue. Tallahassee: Florida Department of Environmental Regulation, Coastal Zone Management Section.

Florida Department of Natural Resources. 1988. *Florida coastal pollutant spill contingency plan*. Tallahassee.

Gales, R. S. 1982. *Effects of noise of offshore oil and gas operations on marine mammals -- An introductory assessment*. NOSC TR 844. San Diego: Naval Ocean Systems Center. Report to the U.S. Department of the Interior, Bureau of Land Management.

Gallaway, B. J., and G. S. Lewbel. 1982. *The ecology of petroleum platforms in the northwestern Gulf of Mexico: A community profile*. FWS/OBS-82/27. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Getter, C. D., S. C. Snedaker, and M. F. Brown. 1980. *Assessment of natural resource damages at the Howard Star oil spill site, Tampa Bay, Florida*. Unpubl. report by Research Planning Institute, Columbia, SC. RPI/R/80-11.

Gilfillan, E. S., D. S. Page, R. P. Garber, S. Hansen, J. Cooley, and J. Hotham. 1981. Fate of the *Zoe Colocotronis* oil spill and its effects on infaunal communities associated with mangroves. In *Proceedings, 1981 Oil Spill Conference*, 353-360. Washington, DC: American Petroleum Institute.

Greeneridge Sciences, Inc. 1985. *A pilot study of possible effects of marine seismic airgun array operation on rockfish plumes*. Report prepared for the Seismic Steering Committee. Santa Barbara, CA.

Harper, D. E., Jr., D. L. Potts, R. R. Salzer, R. J. Case, R. L. Jaschek, and C. M. Walker. 1981. Distribution and abundance of macrobenthic and meiobenthic organisms. In *Environmental effects of offshore oil production. The Buccaneer gas and oil field study*, ed. B. S. Middleditch, 133-177. New York: Plenum Press.

Harris, W. M., and L. Thurston. 1989. *Federal offshore statistics: 1988. Leasing, exploration, production, and revenues*. OCS Rep. MMS 89-0083. Herndon, VA: U.S. Department of the Interior, Minerals Management Service.

Hudson, J. H., and R. Diaz. 1989. Damage survey and restoration of M/V *Wellwood* grounding site, Molasses Reef, Key Largo National Marine Sanctuary, Florida. In *Proceedings, Sixth International Coral Reef Symposium, Townsville*. Queensland, Australia.

Jackson, J. B. C., J. D. Cubit, B. D. Keller, V. Batista, K. A. Burns, H. M. Caffey, R. L. Caldwell, S. D. Garrity, C. D. Getter, C. Gonzalez, H. M. Guzman, K. W. Kaufmann, A. H. Knap, S. C. Levings, M. J. Marshall, R. Steger, R. C. Thompson, and E. Weil. 1989. Ecological effects of a major oil spill on Panamanian coastal marine communities. *Science* 243:37-44.

Johnson, D. 1989. Statement to the Presidential outer continental shelf leasing and development task force, 15 June 1989, Miami, FL.

Kewley, W. 1988. The offshore oil and gas industry's campaign to stop offshore littering. In *Proceedings, Eighth Annual Gulf of Mexico Information Transfer Meeting*, 65-69. OCS Study MMS 88-0035. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Klima, E. F., G. R. Gitschlag, and M. L. Renaud. 1989. Impacts of the explosive removal of offshore petroleum platforms on sea turtles and dolphins. *Mar. Fish. Rev.* 50(3):33-42.

La Liberte, P., and W. M. Harris. 1987. *Federal offshore statistics: 1985*. MMS 87-0008. Washington, DC: U.S. Government Printing Office.

Maciolek-Blake, N., J. F. Grassle, and J. M. Neff, ed. 1985. *Georges Bank benthic infauna monitoring program: Final report for the third year of sampling*. Washington, DC: Minerals Management Service.

Malme, C. I., P. R. Miles, P. Tyack, C. W. Clark, and J. E. Bird. 1985. *Investigation of the potential effects of underwater noise from petroleum industry activities on feeding humpback whale behavior*. Anchorage: U.S. Department of the Interior, Minerals Management Service.

Malme, C. I., P. W. Smith, Jr., and P. R. Miles. 1986. *Characterization of geophysical acoustic survey sounds*. OCS Study MMS 86-0032. Los Angeles: U.S. Department of the Interior, Minerals Management Service.

Malme, C. I., P. R. Miles, G. W. Miller, W. J. Richardson, D. G. Roseneau, D. H. Thomson, and C. R. Greene. 1989. *Analysis and ranking of the acoustic disturbance potential of petroleum industry activities and other sources of noise in the environment of marine mammals of Alaska*. OCS Study 89-0006. Anchorage: U.S. Department of the Interior, Minerals Management Service.

Marszalek, D. S. 1982. *Florida reef tract, marine habitats and ecosystems* (map series). Miami: Rosenstiel School of Marine and Atmospheric Science.

McKenzie, S. 1983. Memorandum to Governor Graham concerning oil and gas exploration leasing in State waters. State of Florida, Office of the Governor. Tallahassee.

Middleditch, B. S., ed. 1981. *Environmental effects of offshore oil production: The Buccaneer Gas and Oil Field Study*. Marine Science Series, Vol. 14. New York: Plenum Press.

Minerals Management Service. 1984. *Environmental assessment for Gulf of Mexico outer continental shelf geological and geophysical activities*. OCS Study MMS 84-0051. New Orleans.

Minerals Management Service. 1987a. *Proposed 5-year outer continental shelf oil and gas leasing program, mid-1987 to mid-1992. Final environmental impact statement*. OCS EIS-EA MMS 86-0127. Washington, DC: U.S. Government Printing Office.

Minerals Management Service. 1987b. *5-Year leasing program, mid-1987 to mid-1992. Detailed decision documents*. Washington, DC: U.S. Government Printing Office.

Minerals Management Service. 1987c. *Final environmental impact statement, proposed oil and gas lease sales 113/115/116, Gulf of Mexico OCS region*. OCS EIS MMS 87-0077. New Orleans.

Minerals Management Service. 1987d. *Programmatic environmental assessment: Structure removal activities, Central and Western Gulf of Mexico Planning Areas*. OCS EIS/EA MMS 87-0002. New Orleans.

Minerals Management Service. 1988a. *Gulf of Mexico Update: July 1986 - April 1988*. OCS Info. Rep. No. MMS 88-0038. Washington, DC: U.S. Government Printing Office.

Minerals Management Service. 1988b. *Pacific outer continental shelf region environmental studies plan, fiscal year 1989*. OCS Rep. MMS 88-0024. Los Angeles.

Minerals Management Service. 1988c. *Gulf of Mexico Sales 118 and 122: Central and Western Planning Areas. Final environmental impact statement*. OCS EIS/EA MMS 88-0003. New Orleans.

Minerals Management Service. 1988d. *Final notice of sale. Outer continental shelf eastern Gulf of Mexico oil and gas lease sale 116, Pt. I*. Washington, DC.

Minerals Management Service. 1989a. *Mid-price scenario, estimates of undiscovered economically recoverable oil and gas resources as of July 1989, Eastern Gulf of Mexico Region*. Document dated 21 September 1989. New Orleans.

Minerals Management Service. 1989b. *Gulf of Mexico sales 123 and 125: Central and Western Planning Areas. Final environmental impact statement*. OCS EIS/EA MMS 89-0053. New Orleans.

Minerals Management Service. 1989c. *Oil & gas leasing/production program: Annual report/FY 1988*. OCS Rep. MMS 89-0055. Washington, DC.

Minerals Management Service. 1990. *Gulf of Mexico sales 131, 135, and 137: Central, Western, and Eastern Planning Areas. Draft environmental impact statement*. OCS EIS/EA MMS 90-0003. New Orleans.

Montgomery, S. L. 1987. Success and sensibility in South Florida. *Pet. Front.* 4(3):1-52.

National Marine Sanctuary Program. 1989. *Status report--November 1989*. Washington, DC: National Oceanic and Atmospheric Administration.

National Research Council. 1983. *Drilling discharges in the marine environment*. Washington, DC: National Academy Press.

National Research Council. 1985a. *Oil in the sea: Inputs, fates, and effects*. Washington, DC: National Academy Press.

National Research Council. 1985b. *Disposal of offshore platforms*. Washington, DC: National Academy Press.

National Research Council. 1989a. *The adequacy of environmental information for outer continental shelf oil and gas decisions: Florida and California*. Washington, DC: National Academy Press.

National Research Council. 1989b. *Evaluation of the hydrocarbon resource estimates for the offshore areas of northern and southern California and Florida south of 26° latitude*. Washington, DC: National Academy Press.

National Response Team. 1989. The *Exxon Valdez* oil spill: A report to the President. Washington, DC: U.S. Department of Transportation and U.S. Environmental Protection Agency.

Neff, J. M., N. N. Rabalais, and D. F. Boesch. 1987. Offshore oil and gas development activities potentially causing long-term environmental effects. In *Long-term environmental effects of offshore oil and gas development*, ed. D. F. Boesch and N. N. Rabalais, 149-173. New York: Elsevier.

O'Hara, K. J. 1988. Education and awareness: Keys to solving the marine debris problem. In *Proceedings, Eighth Annual Gulf of Mexico Information Transfer Meeting*, 70-74. OCS Study MMS 88-0035. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Payne, J. R., C. R. Phillips, and W. Hom. 1987. Transport and transformations: Water column processes. In *The long-term effects of offshore oil and gas development*, ed. D. F. Boesch and N. N. Rabalais, 175-231. New York: Elsevier.

Pearson, W. H., J. R. Skalski, and C. I. Malme. 1987. *Effects of sounds from a geophysical survey device on fishing success*. OCS Study 86-0020. Los Angeles: U.S. Department of the Interior, Minerals Management Service.

Petroleum Industry Response Organization Steering Committee. 1990. *Steering committee report and recommendations on the implementation of PIRO*. Washington, DC.

Phillips, N. W., and B. M. James, ed. 1988. *Offshore Texas and Louisiana marine ecosystems data synthesis*. OCS Study MMS 88-0067. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Reggio, V.C., Jr. (comp.). 1989. *Petroleum structures as artificial reefs: A compendium*. Fourth International Conference on Artificial Habitats for Fisheries, Rigs-to-Reefs Special Session, 4 November 1987. OCS Study MMS 89-0021. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Reinburg, L., Jr. 1984. *Waterborne trade of petroleum and petroleum products in the wider Caribbean region*. CG-W-10-84. Washington, DC: U.S. Coast Guard, Office of Marine Environment and Systems.

Research Planning Institute, Inc. 1983. *The sensitivity of coastal environments and wildlife to spilled oil in South Florida*. Report prepared for the State of Florida Department of Veteran and Community Affairs.

Risotto, S. P., and J. H. Collins. 1986. *Gulf of Mexico summary report/index, November 1984 - June 1986*. OCS Info. Rep. No. MMS 86-0084. Washington, DC: U.S. Government Printing Office.

Robertson, M. J., and W. B. Robertson. 1982. Occurrence and effects of chronic, low-level oil contamination in a population of sooty terns (*Sterna fusca*). Unpubl. manuscript.

Schanck, J. W. 1989. Statement to the Presidential outer continental shelf leasing and development task force, 13 June 1989, Ft. Myers, FL.

Shinn, E. A., and R. I. Wicklund. 1989. Artificial reef observations from a manned submersible off Southeast Florida. In *Petroleum structures as artificial reefs: A compendium*, comp. V. C. Reggio, Jr., 161-173. OCS Study MMS 89-0021. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Shinn, E. A., P. A. Dustan, and B. H. Lidz. 1989. *Biological assessment of the impact of exploratory wells drilled offshore South Florida*. OCS Study MMS 89-0022. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Smith, M. W., and J. L. Hunt. 1979. *Marquesas Key well site survey report*. New Orleans: U.S. Department of the Interior, Bureau of Land Management.

Smithsonian Institution. 1971. *S. I. Event No. 186-70*. Washington, DC: Center for Short-Lived Phenomena.

South Florida Regional Planning Council. 1984. *OCS facility siting study*. Hollywood.

Southwest Florida Regional Planning Council. 1983. *Outer continental shelf onshore facilities siting study*. Ft. Myers.

Spill Response Task Force. 1990. Final report (draft dated 1 February 1990). Tallahassee.

State of Florida, Office of the Governor. 1988. Governor announces historic agreement to protect Keys. Press release dated 24 March 1988. Tallahassee.

State of Florida, Office of the Governor. 1990. Governor announces petroleum industry agreement to protect Florida Keys. Press release dated 19 February 1990. Tallahassee.

State of Florida and Minerals Management Service. 1989a. *Southwest Florida OCS drilling impact assessment task force report*. Prepared for the Governor of Florida and the Secretary of the Interior.

State of Florida and Minerals Management Service. 1989b. *Oil spill risk assessment task force report*. Prepared for the Governor of Florida and the Secretary of the Interior.

Struhsaker, P. 1969. Demersal fish resources: Composition, distribution, and commercial potential of the continental shelf stocks off southeastern United States. *Fish. Ind. Res.* 4:261-300.

Twachtmann, D. 1988. Letter dated 22 November 1988 to Mr. Kent Stauffer, Minerals Management Service, concerning the State of Florida's denial of Coastal Zone Management consistency for UNOCAL's proposed exploratory drilling in the Pulley Ridge area.

U.S. Coast Guard. 1976. *Vessel traffic study in the Straits of Florida*. Miami.

U.S. Geological Survey and Minerals Management Service. 1989. *Estimates of undiscovered conventional oil and gas resources in the United States--A part of the Nation's energy endowment*. Washington, DC: U.S. Government Printing Office.

Voss, G. L. 1988. *Coral reefs of Florida*. Sarasota: Pineapple Press.

Ward, C. H., M. E. Bender, and D. J. Reish, ed. 1979. *The Offshore Ecology Investigation: Effects of oil drilling and production in a coastal environment*. Rice Univ. Studies, Vol. 65, Nos. 4 & 5. Houston, TX.

Williams, J., W. F. Grey, E. B. Murphy, and J. J. Crane. 1977. *Drift bottle analyses of eastern Gulf of Mexico surface circulation*. Memoirs of the Hourglass Cruises, Vol. 4, Pt. III. St. Petersburg: Florida Department of Natural Resources, Marine Research Laboratory.

Wolfson, A., G. Van Blaricom, N. Davis, and G. S. Lewbel. 1979. The marine life of an offshore oil platform. *Mar. Ecol. Prog. Ser.* 1:81-89.

CHAPTER 13
FATE AND EFFECTS OF ROUTINE DISCHARGES: IMPLICATIONS FOR SOUTH FLORIDA COMMUNITIES AND RESOURCES

Alan D. Hart, Paul N. Boothe, and B. J. Presley

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INTRODUCTION

The purpose of this chapter is to discuss the fate and effects of routine discharges in the marine environment and to make informed extrapolations about the fate and effects of these discharges in South Florida if drilling activities commence there in the future.

To date, only limited exploratory drilling has occurred in South Florida (see **Chapter 12**), and there have been few studies of environmental effects of drilling-related discharges in tropical and subtropical habitats. However, considerable information is available from laboratory and field studies in other areas. A National Research Council (NRC) panel reviewed the subject of drilling discharges in the marine environment in the early 1980s (NRC 1983). This subject received a major update at the 1988 International Conference on Drilling Wastes held in Calgary, Alberta (Engelhardt et al. 1989). Other pertinent reviews include Gettleson (1980), Petrazzuolo (1983), Duke and Parrish (1984), U.S. Environmental Protection Agency (EPA) (1985), Dodge and Szmant-Froelich (1985), Neff (1987), and Abernathy (1989).

Routine discharges from oil and gas operations can be divided into those that occur during exploratory and developmental operations (drilling fluids and formation cuttings),

and those that occur during production operations (produced water). Other routinely discharged wastes, such as deck drainage, domestic and sanitary wastes, cooling water, and desalinization brine, are generated by personnel on the drilling rig or platform during both phases of operations.

The first section of the chapter describes the various types of routine discharges and summarizes what is known about their fate in the marine environment. The second section reviews studies of biological effects and evaluates them in relation to South Florida biological communities and resources.

DESCRIPTION AND FATE OF ROUTINE DISCHARGES

Drilling Fluids

Drilling fluids (also known as drilling muds) are generally water-based, thixotropic, colloidal suspensions used during rotary drilling to perform several functions integral to the drilling process. Functions include cooling and lubricating the drill bit and string, transporting formation cuttings to the surface, balancing subsurface and formation pressure, and controlling fluid movement across the borehole wall (EPA 1985; Abernathy 1989). Drilling personnel constantly monitor the characteristics of the drilling fluid during drilling, altering its composition as needed to meet downhole conditions. Barite (barium sulfate) is often added to increase density, bentonite clay is added to increase viscosity, and other components are added to control fluid loss, corrosion, pH, etc. In shallow wells (<1,500 m penetration), drilling fluid composition can be simple. In deeper wells, high temperatures, pressures, friction, and other problems require a more complicated fluid.

Drilling fluids are classified as either water-based or oil-based, depending on their principal liquid phase component. We limit our discussion to water-based drilling fluids, because these are the fluids that are primarily used in outer continental shelf (OCS) wells, and they are the only ones permitted to be discharged on the OCS. Also, for this discussion, drilling fluid components and the formation solids (cuttings) are treated separately.

Despite the large number of trade-name drilling fluid additives, drilling fluids are formulated from only about 55 different chemical compounds; only 10 to 15 of these compounds are used in a typical well. The combination of additives and the chemical and physical interactions within the hole make each drilling fluid somewhat unique. Boothe and Presley (1985) compiled a detailed, comprehensive listing of the components in drilling fluids (**Table 13.1**). The data in **Table 13.1** were compiled from actual mud logs provided by the companies that drilled each well. Barite (barium sulfate), clay, and chromium-containing materials are the three major components (by weight) in drilling fluids. The barite data in **Table 13.1** exhibit a strong positive correlation ($r = 0.92$, $p < 0.01$) with average well depth. That is, deeper wells require disproportionately heavier drilling fluids (i.e., more barite) to balance the increased formation pressures.

After the drilling fluid has circulated through the well and has returned to the surface, it passes through solids control equipment. The solids control equipment removes formation solids (cuttings), which are discharged continuously to the ocean whenever drilling is in progress. We discuss the fate of the discharged cuttings in the next section. After passing through the solids control equipment, the drilling fluid returns to the mud tanks for recirculation. At this point, intermittent, bulk discharges may be required. These discharges are made to maintain important fluid properties, to change the type of drilling fluid, or to dispose of the entire drilling fluid system at the end of drilling. Such intermittent, bulk discharges usually occur every 1 to 3 d during drilling and the volumes vary greatly (15,000 to 150,000 L) depending on the stage of drilling (NRC 1983).

Table 13.1. **Detailed summary of drilling fluid components used in drilling 49 wells in the northwestern Gulf of Mexico between 1970 and 1980 (From: Boothe and Presley 1985).**

Well Site (1)	Number of Wells	Total Amount (10^3kg) of Component Used in All Drilling Activities at Each Site: Barite (2)	Attapulgite Bentonite Clays (3)	Chrome Containing Compounds (4)	Lignitic Material (5)	Caustic Soda (6)	Soda Ash/ Sodium bicarbonate (7)	Lime (8)	Phosphate (9)	Mica and Other Materials (10)	Walnut Hulls, Organic Fibers, Rubber (11)	Cellulose Polymers (12)	Emulsifiers (13)	Surface Active Agents (14)	Defoamers (15)	Lubricants (16)	Diesel Oil (17)	Salt (18)
West Cameron (ES)	2	4,702	587	128	112	53	13.2	7.4	--	17.9	30	7.6	3.6	5.5	0.28	--	--	--
Vermilion 381 (ED)	2	446	106	30	30	20	3.4	1.4	--	2.9	8.6	0.86	--	--	0.07	1.8	--	--
Matagorda (DS)	8	4,547	377	146	56	86	25	7.2	4.2	40	47	6.1	0.48	0.42	0.78	0.70	--	--
High Island (DD)	8	2,957	240	50	13.8	25	2.5	3.8	6.0	47	15.7	6.2	24	37	0.48	46	--	--
Brazos (PS)	4	2,028	80	4.4	66	23	3.9	0.2	5.9	2.6	16.0	--	6.0	7.1	0.15	1.0	--	--
Vermilion 321 (PD)	25	9,671	687	2.0	393	179	4.3	179	0.23	50	74	116	131	26	1.4	1.7	149	270
	Mean Well Depth (m)	Total Amount (kg used/m drilled) of Component Used in All Drilling Activities at Each Site																
West Cameron (ES)	4,422	532	66	14.5	12.6	6.0	1.5	0.84	--	2.0	3.4	0.86	0.41	0.62	0.03	--	--	--
Vermilion 381 (ED)	2,346	95	23	6.4	6.4	4.3	0.73	0.31	--	0.61	1.8	0.18	--	--	0.02	0.38	--	--
Matagorda (DS)	3,117	182	15	5.8	2.3	3.5	1.0	0.29	0.17	1.6	1.9	0.24	0.02	0.02	0.03	0.03	--	--
High Island (DD)	2,993	124	22	2.1	0.58	1.1	0.10	0.16	0.25	2.0	0.66	0.26	1.0	1.5	0.02	1.9	--	--
Brazos (PS)	2,730	186	7.3	0.41	6.1	2.1	0.36	0.02	0.54	0.23	1.5	--	0.55	0.65	0.01	0.09	--	--
Vermilion 321 (PD)	3,116	124	8.8	0.03	5.1	2.3	0.05	2.3	<0.01	0.64	0.95	1.5	1.7	0.33	0.02	0.02	1.9	3.5

(1) Well type designation: Exploratory (E), Development (D), Production (P); Shallow (S), Deep (D) water.
(2) Native barium sulfate ($BaSO_4$). Trade names include Imco Bar, Mil-Bar. Function: weighting material.
(3) Native clay minerals. Trade names include Imco Klay, Imco Gel, Zeogel, Mil-Gel. Function: viscofiers.
(4) Primarily chrome (and ferro-chrome) lignosulfonates and chrome lignite. Trade names include Q-Broxin, Spersene, XP-20, Uni-Cal, Imco VC-10, CL-CLS. Some sodium chromate (Na_2CrO_4) generic compound. Function: thinner and dispersant, filtrate reducer.
(5) Trade names include Carbonox, Ligco, Imco Lig, Tannathin, Imco RD-111. Function: thinner and dispersant, filtrate reducer.
(6) Sodium hydroxide (NaOH). Generic compounds. Function: alkalinity and pH control additive.
(7) Sodium carbonate (Na_2CO_3) and sodium bicarbonate ($NaHCO_3$), respectively. Generic compounds. Function: calcium remover (primary) and alkalinity and pH control additive (secondary).
(8) Calcium oxide (CaO). Generic compound. Function: alkalinity and pH control additive.
(9) Includes sodium phosphate (NaH_2PO_4), sodium tetraphosphate ($Na_5P_3O_{10}$) and sodium acid pyrophosphate ($Na_2H_2P_2O_7$). Trade names include Imco phos SAPP, SAPP, Magco-phos. Function: thinner and dispersant, calcium remover.
(10) Trade names include Diaseal M, Imco myca, Kwik seal, Phenoseal, Imco flakes. Function: lost circulation material.
(11) In fine, medium, and coarse grades. Trade names include Nut plug, Imco plug, Imco fyber, Dick's mud seal. Function: lost circulation material.
(12) Also includes starch materials. Trade names include Mil CMC, Cellex, Imco loid, Mil starch, Drispac. Function: filtrate reducer.
(13) Trade names include Soltex, EZ spot, Imco spot, Clean spot, Super drill, Imco ken-X concentrate. Function: to create a homogeneous mixture of two dissimilar liquids.
(14) Trade names include Milchem MD, Pipelax, Imco SWS, HME, NNE, DMS, Surflo B33. Function: to reduce interfacial tension between contactive water/oil, water/solid, and water/air surfaces.
(15) Primarily aluminum stearate $[CH_3(CH_2)_{16}COO]_3Al$. Generic compound. Includes some other material (e.g., Imco foamban). Function: to reduce foaming action in drilling fluids.
(16) Includes petroleum-based compounds as well as mechanical lubricants such as glass beads and graphite. Trade names include Imco lubrikleen, DLC, Lubraglide, Torq trim, Lubra beads, Bit lube II. Function: friction reduction, freeing stuck drill pipe.
(17) Generic material. Function: thinner and dispersant, lubricant. Used to convert to oil base drilling fluid system for some wells. Not discharged.
(18) Sodium (NaCl) or calcium chloride ($CaCl_2$). Function: emulsion stabilizer.

Wells vary in amount of discharged material, but considering only the quantity of discharged solids (everything but water) minimizes this inter-well variability. About 2,000 metric tons of dry solids are discharged over the life of a typical exploratory well, and as much as 25% less from development wells. Drilling fluid components constitute about half of this amount (NRC 1983). **Table 13.2** gives several estimates of the magnitude of drilling fluid discharges from exploratory, development, and production wells in three different U.S. OCS areas. There is an approximately two-fold range in mean total solids and chromium discharged per well, but a much narrower range in mean barium discharged. The fact that smaller discharges are made from the shallower development and production wells in the Gulf of Mexico explains most of the variation (NRC 1983). EG&G Environmental Consultants (1982) made the best estimate of total trace metals discharged from a well during the Mid-Atlantic Block 684 monitoring program. **Table 13.3** summarizes these estimates, which were based on actual trace metal analyses of the major drilling fluid additives, and representative drilling fluid and solids control equipment discharges. A significant proportion of all metals except chromium came from the cuttings rather than the drilling fluids.

When bulk discharges of drilling fluids occur, two plumes are typically formed: a main or lower plume, and an upper plume. Most of the discharged material forms the lower plume, which descends rapidly to the seafloor near the well site. The distance from the discharge point (within 500 m for most OCS sites with water depths <80 m) depends on water depth, lateral transport, particle size distribution, and density of material. In addition, turbulent mixing of the lower plume with seawater causes formation of a visible or upper plume. The fraction of the total discharge that breaks away from the main plume to form this upper plume is generally <10%. In deeper water (>80 m depending on site conditions), the lower plume will stop sinking (reach neutral buoyancy) before encountering the seafloor. The contents of the upper plume are diluted significantly within a few hundred meters of the discharge point and rapidly transported away by ambient ocean currents (NRC 1983).

The fate of lower plume material after initial deposition on the seafloor depends on environmental factors such as water depth and hydrographic regime. These factors govern sediment resuspension, transport, dispersion, and burial in the sediment column. The dominant components of the lower plume are barite and bentonite clays (average 90% dry weight of the drilling fluid components used, see **Table 13.1**). The lower plume material is transported over time beyond the initial deposition point near the well site, depending on resuspension by waves and currents (NRC 1983; Boothe and Presley 1985). Barium has proved to be an excellent tracer of the settleable (lower plume) drilling fluid components. It is the major component in drilling fluids (up to 47% dry weight) and exhibits low background concentrations in uncontaminated marine sediment (e.g., <50 ppm in carbonate rich sediments typical of the study area--see **Chapter 3**). Drilling fluids are the major anthropogenic source of barium in OCS waters.

Boothe and Presley (1985) conducted a study in the northern Gulf of Mexico in 1980 to determine barium and trace element levels in sediments within 500 m of exploratory, development, and production well sites. These wells were located in both shallow (<34 m) and deep (>76 m) water. Surface and subsurface sampling density was sufficient to permit an accurate, three-dimensional mass balance of discharged barium (in excess of background sediment barium concentrations) to be calculated. **Table 13.4** summarizes the barium mass balance data from the study. These data clearly show that only a small fraction of the total barium used (i.e., <1.5% nearshore, <12% offshore) is present in near-site sediments. Multiple regression analysis of the data suggested that water depth (as an indicator of the magnitude of sediment resuspension and transport) largely controlled the retention of barium in the sediments near the sites. Also, the process of barium transport beyond 500 m was rapid because the percentage of total used barium that was present in the near-site sediments was independent of the length of time between cessation of drilling and sediment sampling.

Table 13.2. Average discharges of particulate solids, barium, and chromium from outer continental shelf wells (From: National Research Council 1983). All weights in metric tons.

Description of Discharge	GOM* Average Well	GOM Five Exploratory Wells	Mid-Atlantic Exploratory Well	Georges Bank Eight Exploratory Wells	GOM 49 Wells
Well depth (m)	5,486	3,329	4,970	4,900	3,121
Total solids	1,140	–	2,160	1,220†	598†
Barite	–	600	752	715	492
Barium§	–	312	391	372	256
Chrome lignosulfonate	–	20	45	26	10
Chromium¶	–	0.6	1.3	0.8	0.3

* GOM = Gulf of Mexico.
† Drilling fluid solids only (does not include cuttings).
§ Barium estimated as 52% of barite weight.
¶ Chromium estimated at 2.9% of chrome lignosulfonate weight.

Table 13.3. Estimated maximum quantity of trace metals discharged from an exploratory well drilled in 1979 off the coast of New Jersey (From: EG&G Environmental Consultants 1982).

Metal	Solids Control Equipment Discharges (kg)	Drilling Fluid Discharges (kg)	Total Metal Discharged (kg)
Cr	78	1,300	1,378
Cd	<2	<3	<5
Pb	12	21	33
Hg	2	3	5
Ni	29	27	56
V	17	41	58
Zn	170	304	474

Table 13.4. Mass balance of total discharged (excess) barium retained in sediments surrounding offshore drill sites (Modified from: Boothe and Presley 1985).

Drill Site*	Type†	Water Depth (m)	Mode of Discharge§	Total Barium Used (TBU) in Drilling Activities (10^3 kg)	Mean BAEXAC 0-500 m Radius (g/m^2)¶	Total Excess Barium (TEB) in Sediments (10^3 kg) within Radius (m)**				Percent of TBU within Radius (m)			
						500	1000	2000	3000	500	1000	2000	3000
West Cameron 294	ES	13	Surface	2,414	25.8	20.3	-	-	131	0.84	-	-	5.4
Vermilion 381	ED	102	Surface	229	28.0	22.0	-	-	193	9.6	-	-	84.0
Matagorda 686	DS	29	Surface	2,334	27.5	21.6	-	-	131	0.93	-	-	5.6
High Island A-341	DD	76	Surface	1,518	173.0	136.0	-	-	1,093	9.0	-	-	72.0
Brazos A-1	PS	34	Surface	1,041	19.2	15.1	-	-	70	1.5	-	-	6.7
Vermilion 321	PD	79	Surface	4,964	759.0	596.0	-	-	2,330	12.0	-	-	47.0
High Island A-502	ED	55	Shunted	127	8.8	6.9	21	-	-	5.4	16.5	-	-
Mustang Island A-85	ED	75	Shunted	820	14.0	11.0	31	-	-	1.3	3.8	-	-
High Island A-367	ED	95	Surface	574	12.7	10.0	19	46	90	1.7	3.4	8.1	16.0
High Island A-384	ED	112	Shunted	396	143.0	117.0	129	161	-	30.0	33.0	41.0	-
High Island A-389	ED	124	Shunted	618	43.3	34.0	78	-	-	5.5	12.6	-	-
Mid-Atlantic (18-3) 684	ED	120	Surface	443	8.2	6.4	16	42	86	1.5	3.7	9.5	19.0

* All sites are in the northwest or north central Gulf of Mexico except Mid-Atlantic 684, which is off the coast of New Jersey.
† Exploratory (E), development (D), or production (P) in shallow (S) or deep (D) water.
§ Shunted discharge pipes were located within 10 to 15 m of the seafloor.
¶ Mean total excess barium in the sediment column areal concentration (BAEXAC) within a 500-m radius of the drill site = $TEB_{500}/2\ pi(500)^2$.
** All TEB data for the first six sites were estimated using the procedure described in Boothe and Presley (1985). For the remaining six sites, all TEB are based on actual samples. However, to avoid underestimating TEB beyond 500 m, which could result from a combination of low sample density and patchy distribution of excess Ba, a minimum BAEXAC value of 1.5-3 g/cm^2 was used for the area where BAEXAC was calculated to be zero.

The long-term fate of the lower plume particulates, once transported beyond the immediate vicinity of the drill site, is unknown. Bentonite clays presumably are transported and dispersed until they reach areas of net sediment accumulation (sediment sinks). Unless unusual current conditions (i.e., those caused by hurricanes or other strong storms) remove the clays from such sink areas, they will be buried eventually and incorporated into the sediment column. Barite particulates will be dispersed similarly, allowing for barite's greater density compared with clay. However, because seawater is undersaturated with respect to barite, some amount of dissolution of this phase should occur between discharge and eventual burial (NRC 1983). Boothe and James (1985) analyzed surface and subsurface sediment samples from more than 80 stations (>300 analyses) across the Texas-Louisiana continental shelf for barium. Surface and subsurface sediment barium enrichments (above natural background levels) were consistently much smaller (i.e., averaging <160 ppm) than would be expected (i.e., >2,500 ppm in the upper 4 cm) if all discharged drilling fluid barium had been retained in the study area. Some combination of large-scale dissolution and off-shelf transport of fine sediments is the most likely explanation for the low retention of discharged barium in shelf sediments (Boothe and James 1985). Other drilling fluid components also would be expected to become incorporated to varying degrees in the sediment column over a wide area from the discharge point.

The location of a well site in restricted versus unrestricted waters will largely determine the fate of any future drilling fluid discharges in the study area. The South Florida continental shelf is the dominant geographic feature within the study area, which also includes a portion of the Southwest Florida shelf to the north. The South Florida shelf margin is the only area of the continental U.S., and one of the few areas in the world where shallow-water (generally <12 m water depth), marine carbonate sediments are actively being deposited on a large scale. Natural subdivisions of the South Florida shelf are the restricted inner shelf (Florida Bay), the slightly restricted inner shelf margin (Hawk Channel), the outer shelf margin where circulation and turbulence are maximum, and the shallow slope seaward of the shelf break. The Florida Keys, a gradually arching chain of islands extending southward from Soldiers Key south of Miami Beach to the Dry Tortugas, form the border between Florida Bay and Hawk Channel (see **Chapter 2**). The division between the inner and outer shelf is the Florida Reef Tract, a continuous band of coral reefs 4.8 to 11.3 km (2.6 to 6 nmi) offshore, bordering the Straits of Florida and the Atlantic Ocean (Enos and Perkins 1977).

In the open, unrestricted, continental shelf waters of the study area, the fate of discharged drilling fluids should be similar to that described above for the Texas-Louisiana continental shelf in the northern Gulf of Mexico. Such open-shelf waters include those of the West Florida shelf and those of the Straits of Florida, including both the outer shelf margin and the shallow slope seaward of the shelf break. In these areas with significant circulation and turbulence, drilling fluid particulates, initially deposited on the seafloor in the immediate vicinity of the drill site, will be rapidly (time scale of months to a few years) dispersed over a wide area. The sediments in these areas are generally bare sand with <10% fine-grained material (fines) (<62 μm). Strong currents have winnowed the fines away and dispersed them to sediment sinks, generally in deeper continental slope waters. The expected increases in sediment concentrations of barium, clay, and other drilling fluid components should be small. However, because the natural background levels of these materials are very low, any increase should be easily observed, especially if both the bulk and fine fractions of the sediment are analyzed. Also, the retention of discharged barium, and other similarly behaving drilling fluid components, in sediments near the well site should be small (i.e., ≈1% nearshore, and 10 to 15% offshore).

However, in the restricted waters of the inner shelf (e.g., Florida Bay and Hawk Channel), the dispersion of discharged drilling fluids would be limited. Florida Bay is an embayment of the Gulf of Mexico, with an extensive network of carbonate mudbanks and vast seagrass beds. Semi-restricted circulation with moderately turbid water and thick seagrass cover characterizes the inner shelf margin (Hawk Channel). Hawk Channel sediments are the muddiest of the entire shelf margin (10 to 50% fines), and those of Florida Bay are muddier still. Sediment transport is probably at a minimum on the featureless, level, seagrass-covered muddy bottoms of the inner shelf margin (Hawk Channel). Once sediment is deposited in the seagrass baffle (sink), it is reworked little except by organisms. Also, the inner shelf has the lowest sedimentation rates in the area, with accumulation rates (e.g., 0.18 m/1,000 years) <20% of those on the outer shelf. The average sediment thickness on the outer shelf margin is 3 to 5 times that on the inner shelf margin (Enos and Perkins 1977).

Under these conditions, drilling fluid discharges on the inner shelf would tend to accumulate in sediment sinks near the well site. There, they would reach much higher concentrations than in more open areas. As described by Shinn (1988), during stormy periods, the water throughout the Florida Reef Tract can become turbid from suspended lime mud. When quiet conditions return, this mud settles out everywhere but remains only in sediment sink areas. Mud may settle on the reef when the sea is extremely calm, but the prevailing winds and wave action, quickly resuspend and transport it elsewhere. If the mud settles in deeper, quieter areas such as Hawk Channel, it is likely to be trapped and bound there by extensive meadows of turtle grass. Mud is as much as 6 m thick in some areas of Hawk Channel. During storms, some of this mud is resuspended, only to be deposited eventually in yet another sink. The sink, other than the depths beneath the Gulf Stream, is within the reef itself, where the mud filters down into the reef framework.

Cuttings

Cuttings are small pieces of the subsurface formation that result from the chipping and crushing action of the drilling bit. They range in size from a few micrometers up to several centimeters. A primary function of the circulating drilling fluids is to carry cuttings away from the drilling bit to the surface for disposal. The amount, size, and composition of drilled solids in the drilling fluid affect the rheological properties and penetration rate of drilling fluids. The drilled solids also adversely affect pipe and equipment wear, cause damage to producing formations, and affect the cost of the well. The continuous removal of these solids is essential to a successful drilling fluid system (Imco Services 1978).

Mechanical solids control equipment, consisting of shale shakers and hydrocyclone desanders, desilters, and mud cleaners, is the primary means of avoiding buildup of drilled solids in the drilling fluid. The function of the solids control equipment is to remove the cuttings from the drilling fluid without also removing uneconomically large amounts of important drilling fluid components such as barite. Since 97% of barite is by American Petroleum Institute specifications <74 μm (200 mesh), most of the removed solids are sand-sized or larger (i.e., >74 μm). Cuttings are discharged continuously while drilling is in progress, and up to 1,000 metric tons of cuttings are discharged from each well (NRC 1983).

Because of their generally larger size, discharged cuttings settle rapidly near the well site. Soluble and particulate drilling fluid additives adhering to the cuttings are to some extent washed off as the larger particles settle through the water column. However, significant amounts of fluid additives can remain on the cuttings (NRC 1983). Boothe and Presley (1985) speculated that much of the barium retained in sediment within

500 m of drill sites represented barite adhering to cuttings that were too large to be transported away.

The fate of discharged cuttings in the study area would be similar to that discussed above for discharged drilling fluids. In the restricted waters of Florida Bay, the Florida Keys, and Florida Reef Tract, the cuttings should become part of the sediment column very near any well site. However, in the unrestricted waters of the West and South Florida shelves, the cuttings, because of their larger size, would tend to be dispersed less widely from the point of discharge. During their survey of previous well sites near the Marquesas Keys and off the west coast of Florida, Shinn et al. (1989) noted the absence of cuttings piles around drill sites, but they did detect cuttings in the sediment column after microscopic examination of sediments.

Produced Water and Underwater Gas Discharges

Two types of routine discharges (produced water and natural gas) can be considered byproducts of oil and gas production operations. These discharges could occur if commercially recoverable quantities of hydrocarbons were discovered and developed in the study area.

Variable amounts of produced water (also called formation water, or brine) coexist with petroleum in subsurface geologic reservoirs. Some produced water accompanies any gas or oil removed from the reservoirs. The amount of such water produced with petroleum varies considerably, depending on the oil-bearing formation and age of the well. New wells may produce almost no water, while old ones often produce more than 90% water (Collins 1975). The volume of produced brines varies with well location, field characteristics, and production methods. Offshore oil production platforms may discharge up to 1.5 million liters of produced water per day (Neff 1987). Gas-producing wells coproduce much smaller volumes of formation waters than do oil-producing wells.

Although the composition of produced water is similar to that of seawater, characteristic differences include elevated salinity and altered ion ratios; elevated temperature; low dissolved oxygen; increased biochemical oxygen demand; and contamination with petroleum hydrocarbons, other organic compounds, trace metals, and radionuclides (Rose and Ward 1981; EPA 1985; Neff 1987).

The trace element composition of produced water varies considerably and can be difficult to determine accurately. Neff et al. (1989b) performed the most complete chemical analyses of produced water. They analyzed produced water samples from two sites in Louisiana in detail. Salinities of the produced water samples ranged from 143 to 220 ppt. A number of organic compounds, including priority pollutants, were found. Total organic concentrations (including volatile organics and polycyclic aromatic hydrocarbons) were about 8 to 19 mg/L at the two sites. The most abundant of the analyzed metals were barium, lead, and zinc. These metals were present in concentrations three orders of magnitude greater than generally found in seawater.

Radium concentrations are higher in subsurface brines than in other natural waters (Kraemer and Reid 1984). Based on the salinity values, Neff et al. (1989b) concluded that the produced waters they analyzed contained less radium than would be expected from the data of Kraemer and Reid. Despite the elevated levels of radionuclides in produced waters relative to seawater, it is likely that the rapid dilution of the waters when discharged precludes significant accumulation in ambient biota or sediment. However, the authors are not aware of any study that has investigated the fate of discharged radionuclides and confirmed the hypothesis of no accumulation.

Upon discharge, produced water should behave like the upper (buoyant) plume formed during drilling fluid bulk discharges. As discussed above, this plume is rapidly (<1 h) diluted by ambient currents. Dilution ratios of more than a million-fold have been observed within a few hundred meters of the discharge point (NRC 1983). This has been tested by a large environmental monitoring study conducted by the Department of Energy (DOE) from 1978 to 1985. Formation waters (brine) from the Strategic Petroleum Reserve (SPR) were discharged through large offshore diffusers at sites on the Texas and Louisiana continental shelf. The purpose of this DOE study was to assess the environmental impact of this disposal. Water column, sediment, and organism samples were taken regularly at both the West Hackberry (offshore Cameron, LA) and the Bryan Mound (offshore Freeport, TX) sites. Analysis of these samples showed that dilution of the brine was so rapid that enhanced salinity levels were only observed in the immediate vicinity of the diffuser. Based on comparisons to control sites, brine disposal did not appear to have any significant influence on trace element levels in the water column, sediment, or biota in the vicinity of the diffuser (Hann et al. 1985).

Based on the above discussion, produced water discharged into open waters in the study area should be diluted rapidly by local currents. Components of the brine should not accumulate in ambient biota or sediment. This conclusion is certainly valid for unrestricted South Florida waters, which have current regimes similar to those of the two DOE/SPR study sites. In the more restricted waters of Florida Bay and Hawk Channel, the flushing rate may be sufficient to prevent any persistent increases in brine components in the surrounding environment.

During offshore production operations, pressure decreases that occur during oil recovery cause the release from solution of gas associated with oil in formation reservoirs. This gas is sometimes burned off (flared) and sometimes released underwater (vented). Brooks et al. (1977) examined the effects of underwater gas venting on water column hydrocarbon concentrations on the northwestern Gulf of Mexico continental shelf. They used continuous extraction of dissolved gases from solution followed by gas chromatography (hydrocarbon "sniffing") to determine the hydrocarbon concentrations. Light hydrocarbons (C_1 to C_4) were generally associated with this gas, but longer chain hydrocarbons (up to C_{15}) were also observed. The investigators concluded that spatial surface distributions of low-molecular-weight hydrocarbons on the Louisiana shelf were largely controlled by proximity to production platforms. These discharges can therefore serve as a source for low-molecular-weight hydrocarbons from production facilities. The investigators also observed that the underwater venting of associated gas was responsible for some overturning of the water column.

Deck Drainage, Domestic and Sanitary Wastes, Cooling Water, Desalinization Brine, and Other Miscellaneous Wastes

Several other discharges occur routinely during oil and gas operations. These include discharges of deck drainage, domestic and sanitary wastes, cooling water, and desalinization brine.

Deck drainage comprises all effluents resulting from platform washings, deck washings, and runoff from curbs, gutters, and drains including drip pans and work areas (Abernathy 1989). A typical offshore drilling rig is equipped with pans to collect deck and drilling floor drainage (EPA 1985). Oil and grease are the primary concern from contaminated deck drainage. This drainage is collected by a separate drainage system and treated for solid removal and oil/water separation; the separated oil is held for onshore disposal (Abernathy 1989).

The largest volumes of domestic and sanitary wastes are generated during the drilling phase of oil and gas production when manpower needs are highest (EPA 1985). Domestic wastes consist of fresh water used for cooking, drinking, and washing (e.g., discharges from sinks, showers, and laundry facilities), and are treated before discharge (Abernathy 1989). EPA regulations cover discharges of sanitary wastes (Abernathy 1989). Pollutant concentrations in sanitary effluents cannot exceed the regulatory criteria. The minimum chloride residue must be of 1.0 ppm, and chloride residue must be maintained as close as possible to this concentration to limit production of quantities of chlorinated compounds. Discharges of this sort are rapidly diluted and dispersed in the receiving waters; suspended solids (organic materials) and biochemical oxygen demand may increase very near the discharge point (Abernathy 1989).

Discharged cooling water may create a local elevation in temperature of the receiving waters because its temperature can be slightly higher than that of the ambient seawater. Similarly, brine produced during desalinization may locally affect salinity. Changes in the receiving waters are probably minor and localized immediately near the discharge because the volume of these discharges is low and rapidly dispersed.

Some miscellaneous wastes discarded from offshore petroleum drilling platforms can have definite local effects on sediment trace element levels. For example, welding rods and other similar metallic debris have been observed in sediments surrounding drilling platforms. Such debris is a likely explanation for the occasional "outlier" sediment samples observed in many rig monitoring studies. Such sediment samples have levels of zinc and other trace elements that are much higher than those in any neighboring samples.

EFFECTS OF ROUTINE DISCHARGES

Discharges occurring during drilling and production operations could affect South Florida biota in various ways. These effects generally have either a physical or a chemical mode. As discussed above, major discharges occurring during exploratory and development drilling are drilling fluids and cuttings. Produced waters are routinely discharged during production operations. Other discharges, such as deck drainage, domestic and sanitary wastes, cooling water, and desalinization brine are also of concern.

Toxicity

Drilling Fluids

Reviewers of results from laboratory bioassays performed to determine toxicity of used drilling fluids and drilling fluid components (NRC 1983; Petrazzuolo 1983; EPA 1985; Neff 1987) have generally agreed that drilling fluids discharged into the marine environment have little potential for acute toxicity to marine organisms. This conclusion is based on two factors. First, bioassay results indicate that used drilling fluids are non-toxic (LC_{50} >100,000 ppm) or practically non-toxic (LC_{50} between 10,000 and 100,000 ppm) (LC_{50} is the concentration of used drilling fluid that kills 50% of the test organisms in a bioassay, generally conducted for 96 h). Second, dispersion, particularly in the open ocean, is sufficient to reduce concentrations of discharged drilling fluids by factors of 1,000 to 10,000 within short distances of the discharge point.

The NRC (1983) concluded that biological effects of drilling discharges are restricted primarily to the benthos. They pointed out that exposure during laboratory bioassays is usually continuous for 96 h. Discharges of large quantities of used drilling fluids do not occur continuously during drilling, so field exposures are commonly <96 h for many biotic components of an ecosystem (e.g., water column assemblages); laboratory bioassays are therefore somewhat unrealistic as models of exposure in the field because

concentrations used in the laboratory often exceed those observed from actual discharges, with the possible exception of the region located very near the discharge point. However, these reviewers qualify their conclusions with respect to specific environments, e.g., shallow, low-energy environments where persistent exposure may occur, as compared with open-water environments.

Petrazzuolo (1983) attempted to relate laboratory bioassay results to the field, using the model of water column dispersion developed for discharge drilling effluents by Auble et al. (1982). Assuming a 15 cm/s current, dispersion of 10^4 would be expected to occur within 100 m of the discharge; assuming a 150 cm/s current, a similar level of dispersion would occur 1,000 m downcurrent of a discharge. In his hazard assessment for effects in the water column, Petrazzuolo's analysis indicated that concentrations equivalent to 100% of the LC_{50} values for all tested drilling fluids and species would be attained within 11.1 min (or about 100 m assuming a 15 cm/s current). Petrazzuolo assumed that chronic effects would occur at concentrations of roughly 1% of the laboratory-measured LC_{50}s. The results of this analysis indicated that the chronic criteria (1% of LC_{50}) would be attained within 2,200 m of the discharge. Based on his review and analysis of community-level effects, Petrazzuolo surmised that drilling effluent discharges from exploratory activities would affect the composition of benthic communities in the near-field (300 m); these effects may be induced by chemically and/or physically mediated means. Effects would generally be restricted to decreases in abundances, and community structure also might be affected as a result.

Neff (1987) concluded that discharged drilling fluids are generally not acutely toxic to marine organisms. Ninety percent of 72 drilling fluids tested using 62 marine species were considered practically non-toxic (LC_{50} >10,000 ppm). The results Neff reviewed were over a broad taxonomic spectrum of organisms. Larval, juvenile, and molting crustaceans were thought to be more sensitive to drilling fluids than most other life stages and species. Based on field studies of dispersions of drilling fluid discharges (**Figure 13.1**), the dilution of discharged drilling fluids is often 1,000-fold within 1 to 3 m of the discharge point; low concentrations would be expected 1,000 to 2,000 m downcurrent within 2 to 3 h.

Neff (1987) also concluded that most of the major ingredients of drilling fluids have low toxicity to marine organisms. Barite and bentonite clays are practically inert toxicologically; only chrome or ferrochrome lignosulfonate and sodium hydroxide are considered moderately toxic. The effects of sodium hydroxide, which alters pH, are temporary and localized because of the buffering capacity of seawater. Chromium in discharged drilling fluids occurs almost exclusively as the trivalent form and is tightly associated with lignosulfonate-clay complexes (NRC 1983; Neff 1987). Trivalent chromium salts have low solubilities in seawater and have low toxicity (NRC 1983). Hexavalent chromium has been shown to be toxic to grass shrimp, but the toxicity was reduced with increasing salinity (Rao et al. 1985).

Diesel fuel, which is sometimes added as a lubricant to drilling fluids, severely increases its toxicity (EPA 1985; Neff 1987). Positive correlations between diesel concentrations in drilling fluid and the toxicity of the drilling fluid have been observed. Breteler et al. (1985) investigated changes in acute toxicity of a non-toxic generic drilling fluid resulting from additions of mineral oil, and low-sulfur and high-sulfur diesel oil. The test organisms were the clam *Mya arenaria*, the sandworm *Nereis virens*, and grass shrimp *Palaemonetes* spp. (*P. pugio* and *P. vulgaris*). Toxicity increased with progressive additions of mineral oil and diesel oils. Diesel oils were more toxic than mineral oil at similar concentrations. Boehm et al. (1989) concluded that, under realistic field conditions, a significant amount of added diesel will be volatilized and that transport to the sediments is likely a minor process.

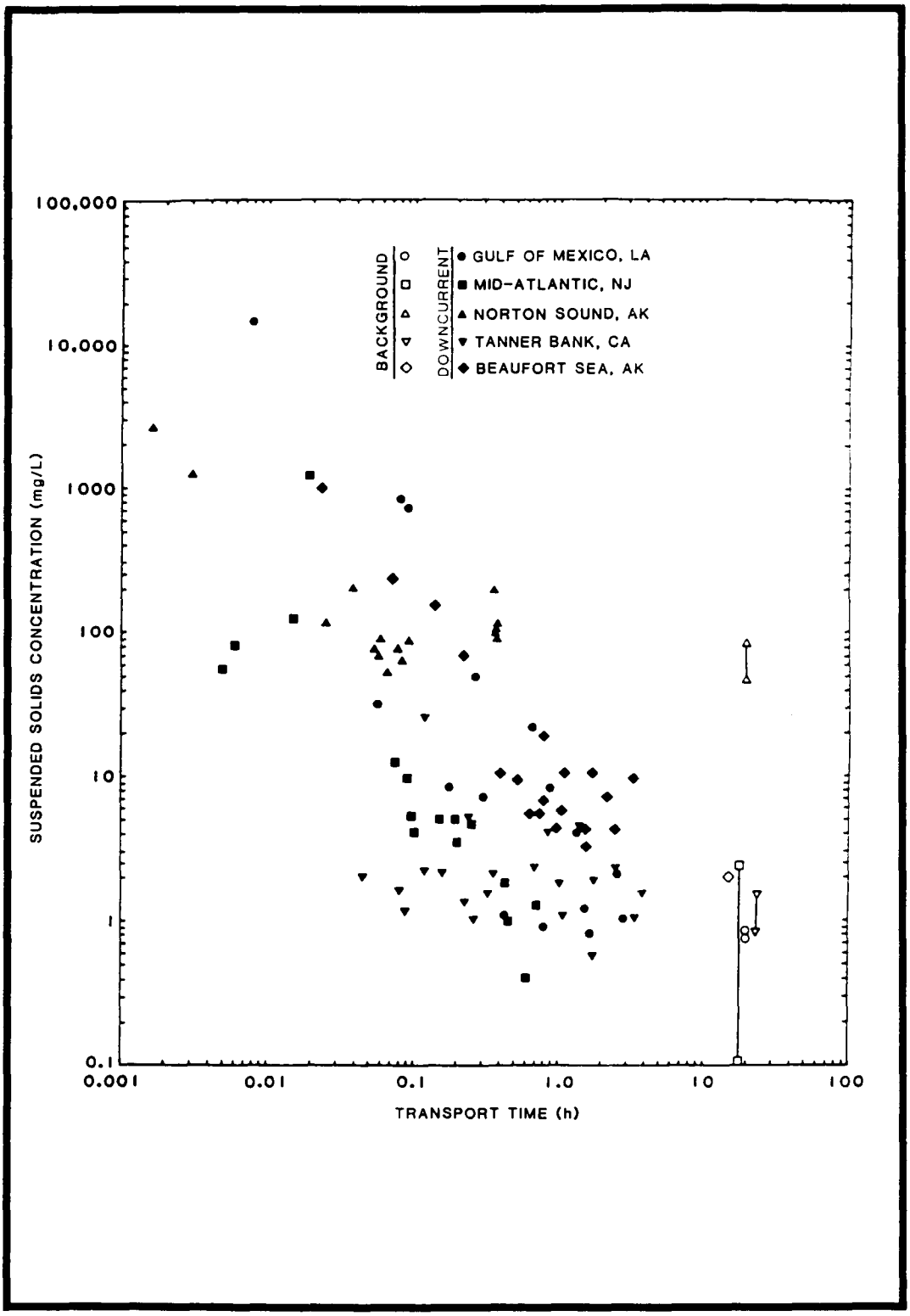

Figure 13.1. Drilling fluid dispersion as a function of transport time (distance from rig divided by current speed) for various areas of the U.S. outer continental shelf (From: Neff 1987). Drilling fluids contained from 200,000 to 1,400,000 mg/L suspended solids before discharge.

The Gulf of Mexico General National Pollutant Discharge Elimination System (NPDES) Permit issued by the EPA in 1986 prohibited the discharge of drilling fluids that contain diesel, except for conditions related to the use and recovery of diesel pills. A pill is a volume of oil-based drilling fluid that is pumped down the drill string and up the annulus of the borehole to the sticking point. The pill serves to weaken the bond between the filter cake on walls of the borehole and the drill string. Recovery involves removing the pill proper and 50 barrels of drilling fluid on either side of the pill.

The EPA's Industrial Technology Division, the American Petroleum Institute, and Gulf of Mexico permittees jointly funded a Diesel Pill Monitoring Program to investigate recovery of diesel pills spotted to free stuck pipe (Ayers et al. 1989). Diesel recovery was calculated using the difference between the quantity of diesel added to the drilling fluid system and the quantity of diesel remaining in the active drilling fluid system after two complete circulations following pill recovery. The results of the study indicated that mean and median recovery rates for diesel were 76.5% and 83%, respectively. Bioassay testing indicated that drilling fluid toxicity increased with increasing diesel content.

At present, the Diesel Pill Monitoring Program has been concluded, and drilling fluids that contain added diesel cannot be discharged into the receiving marine waters (L. Wise, pers. comm. 1990, EPA Region IV, Atlanta). The EPA has proposed new regulations concerning discharges of drilling fluids containing diesel oil (40 CFR Part 435). Comments to these proposed regulations are currently being received and final regulations are not expected for some time. The proposed regulations would prohibit the discharge of drilling fluids containing diesel in detectable amounts. The EPA proposes to regulate diesel at the "best available technology" level to control the amounts of individual toxic organic compounds that diesel contains. These compounds include benzene, toluene, naphthalene, phenanthrene, fluorene, and phenol. Diesel also can contain polynuclear aromatic hydrocarbons such as methylnaphthalene, dimethylnaphthalene, and methylphenathrene. The EPA proposes to use diesel as an indicator for the individual toxicants because it is not technologically feasible to define limitations for all potentially toxic organic pollutants.

The issue of chronic and sublethal toxicity of drilling effluents to marine biota has also been studied. Such effects could be important if the survival of the organism were jeopardized (e.g., if the organism became more susceptible to predation, or had its fecundity reduced). Such effects, not detected in acute toxicity bioassays, could, over sufficient time, affect community structure. Neff (1987) summarized chronic and sublethal responses of marine animals to water-based chrome or ferrochrome lignosulfonate drilling fluids (**Table 13.5**). In most of these laboratory studies reviewed by Neff, conditions of exposure did not closely simulate conditions that would be expected during actual discharges. Either the concentrations were greater in the laboratory than during actual discharges, or exposure duration was much longer than would be encountered. Drilling fluids eliciting sublethal responses at very low concentrations (in comparison with acutely toxic levels) were those that were heavily treated with chromate and diesel oil.

Derby and Capuzzo (1985) reviewed studies of the physiologic and behavioral effects of drilling fluids on marine crustaceans (**Table 13.6**). Concentrations in the aqueous fractions that elicited sublethal effects ranged from 0.1 to 66 g/L drilling fluid over exposure periods of 24 to 96 h. Sublethal responses to whole, used drilling fluids ranged from 7.7 mg/L to 50 g/L over exposure periods of 3 min to 20 d. The authors concluded that much of the toxicity of drilling fluids was associated with the soluble fraction; larval, juvenile, and early post-ecdysis adult crustaceans were more sensitive. The presence of bactericides and diesel oil in drilling fluids (both now prohibited from ocean discharge) influences the degree of toxicity.

Table 13.5. Summary of chronic and/or sublethal responses of marine animals to water-based chrome or ferrochrome lignosulfonate drilling fluids. The lowest exposure concentrations eliciting a response are given (Adapted from: Neff 1987).

Animals	Nature and Length of Exposure	Responses
Reef corals (10 species)	2 mm-12 cm layer for up to 10 h; 1-1,000 ppm suspension for 4-42 d	Polyp retraction; mucus production; expulsion of zooxanthellae; depressed respiration, NH_3 excretion and uptake, photosynthesis, calcification and growth; altered biochemical composition; bacterial infection; death
Bivalve molluscs (6 species)	50-33,000 ppm suspension for 3-100 d	Decreased filtration, byssus thread formation, NH_3 excretion, shell growth, condition index; increased respiration; altered free amino acid ratios, behavior
Crustaceans (15 species)	7.7-100,000 ppm suspension for 5 min-42 d; 1-7 mm layer for up to 4 d	Decreased chemosensory response; inhibition of feeding; altered behavior in larvae and juveniles; cessation of swimming in larvae; increased duration of larval and juvenile development; decreased or increased enzyme activity; gill histopathology; decreased long-term larval and juvenile survival
Polychaete worms (1 species)	10 ppm suspension for 100 d	33% mortality
Echinoderms (5 species)	10-100,000 ppm suspensions for 2 d through duration of larval development	Depressed fertilization; decreased development rate; increased incidence of development anomalies
Teleost fish (3 species)	3,800-30,000 ppm for duration of embryo development; 7-17 mL/L for 3-12 d	Decreased development rate; depressed embryonic heart beat; developmental anomalies; gill histopathology; altered feeding and avoidance behavior; decreased growth

Clark and Patrick (1987) examined sublethal effects of four used drilling fluids and barite incorporated into sediments on the lancelet *Branchiostoma caribaeum*. Acute toxicities were less than for drilling fluids on mysids in water column exposures. These investigators observed reduced burrowing of lancelets exposed to drilling fluid/sediment mixtures. They concluded that a population could be as severely affected by reduced burrowing as by acute toxic effects. They felt that exposure to predation could be increased; however, concentrations at which this behavioral response was observed would only occur in the immediate vicinity of a discharge point.

As part of an experiment to study bioaccumulation, food chain transfer, and the biological effects of discharged drilling effluent, Neff et al. (1989a) exposed juvenile American lobsters (*Homarus americanus*) and juvenile winter flounder (*Pseudopleuronectes americanus*) to contaminated sediments for 99 and 98 d, respectively. The settleable fraction of a heavily treated lignosulfonate freshwater drilling fluid was obtained from an offshore platform in the Gulf of Mexico. It was mixed with natural, fine-sand sediments to obtain a concentration of 9,000 ppm barium. Mortalities of juvenile winter flounder were low and did not differ between tanks containing uncontaminated and contaminated sediments. Higher mortalities were observed in juvenile lobsters exposed to contaminated sediments. This indicated that juvenile lobsters exposed to contaminated sediments were moderately stressed compared with the control group.

Table 13.6. Sublethal effects of drilling fluids on crustaceans (Adapted from: Neff 1987).

Species	Fraction*	Drilling Fluid Concentration (g/L)	Exposure Period	Sublethal Effect
Acartia tonsa (adults)	A	1	72 h	Decreased fecundity
Cancer irroratus (larvae)	A	0.1	96 h	Decreased feeding rates
Cancer irroratus (adult tissue)	A	66	96 h	Increased glucose-6-phosphate dehydrogenase activity
Homarus americanus (larval stage I)	W	0.05	96 h	Decreased respiration rate; decreased dry weight; decreased scope for growth; decreased O:N ratios†
Homarus americanus (juveniles)	W	0.0077	20 d	Decreased food detection ability; decreased molting frequency
Homarus americanus (adults)	W	0.01	3-5 min	Interference with chemosensory processes
Mysidopsis almyra (juveniles)	A	35	24 h	Increased respiration rate; decreased dry weight; decreased scope for growth
Onisimus sp. (adults)	W	50	15 d	Increased Cr, Cd, Pb, Zn content

* A = aqueous fraction of used, whole drilling fluid; W = used, whole drilling fluid.
† O:N refers to the atomic ratio of oxygen consumed to NH_4^+-N excreted.

Produced Water

Rapid dilution of discharged produced water with seawater upon discharge precludes significant toxic effects of produced water in the open ocean (Neff 1987). In shallow-water areas with restricted circulation, there is a greater potential for biological effects.

Gallaway (1981) reviewed the results of the Buccaneer Gas and Oil Field Study, a multidisciplinary investigation of a multi-well producing field off the Texas coast. Gallaway concluded that direct effects of produced waters were restricted to within a few meters of the outfall. Payne et al. (1987) stated that produced waters are rapidly diluted within the immediate vicinity of an ocean outfall; significant increases in water concentrations of dissolved and particulate hydrocarbons and trace metals due to produced water discharges occur within the initial mixing zone or immediate vicinity of the discharge source. Particulate scavenging, advection, evaporation of lower molecular weight aliphatics, and additional weathering processes promote rapid removal of produced water-associated metals and hydrocarbons. Long-term discharges of produced water may result in increases in the sediments in the near field as trace metals and hydrocarbons associated with the discharge may be scavenged from the water column and subsequently deposited within the sediments near the discharge point. However, it should be noted that in shallow-water, low-energy environments where flushing is reduced, produced waters have been detected 1,000 m from the discharge point (Boesch and Rabalais 1989).

Rose and Ward (1981) performed the most extensive laboratory work on the acute toxicities of produced water. These investigators determined LC_{50}s of produced water from the Buccaneer Gas and Oil Field. Rose and Ward performed bioassays using the brown shrimp *Penaeus aztecus* (larva, subadult, and adult), the white shrimp *P. setiferus* (subadult and adult), the barnacle *Balanus tintinnabulum*, and the crested blenny *Hypleurochilus geminatus*. LC_{50}s were generally over 10,000 ppm produced water, and larval brown shrimp tended to be more sensitive than the other species.

Rose and Ward (1981) also evaluated the potential hazards associated with discharged formation water to biota around outfalls. They determined the limiting permissible concentration over time, using the results of the bioassays for the most sensitive test organism (larval brown shrimp). They compared these results with environmental concentrations of produced water in a Lagrangian assessment. The Lagrangian assessment was used to evaluate exposures of organisms such as plankton, which move with currents; such organisms may be initially exposed to high concentrations of produced water, but the concentration would be reduced over time due to dispersion as the water moves away from the discharge point. These investigators concluded that discharged formation water did not represent a potential hazard to plankton drifting through the wastewater plume. The investigators also performed an Eulerian assessment, using 50 ppm as the limiting permissible concentration (independent of exposure time). An Eulerian assessment was used to evaluate exposures to sessile or immobile organisms, i.e., those attached to or living on a substrate, which may reside at a fixed distance from the discharge point. From this analysis, they concluded that discharged formation water was not a potential hazard to benthic and structure-associated organisms living 100 m from the outfall. They felt that the potential hazard may only exist in the near vicinity of the discharge point.

Neff (1987) reviewed the results of acute lethal bioassays of produced water, including those of Rose and Ward. He found that 88% of the bioassays indicated that produced water is practically non-toxic (>10,000 ppm).

Armstrong et al. (1979) studied the effects of brine effluent on the benthic community in a restricted embayment (Trinity Bay, TX). The source of the brine was a separator platform. The depth of the bay varied from 2 to 3 m, and the outfall was 1 m from the seafloor. Sediment naphthalene concentrations and numbers of benthic infaunal species and individuals were determined. The investigators observed a definite correlation between sediment naphthalene concentration and number of species and individuals. The seafloor was almost devoid of organisms within 15 m of the outfall, and the fauna was severely depressed 150 m away. The investigators estimated that concentrations of total naphthalenes must exceed 2 ppm to significantly reduce benthic infaunal populations at the Trinity Bay study site. At stations located farther from the discharge site (385 to 1,675 m), the infaunal assemblage was enhanced, in terms of numbers of individuals and number of species, compared with the reference stations located 4,000 to 5,800 m away. The investigators cautioned against applying these results to offshore production sites because the greater water depths and lower concentrations of suspended sediments in offshore areas would result in a smaller fraction of hydrocarbons being deposited in the sediments surrounding an outfall; effects on the infauna would be correspondingly reduced.

Sedimentation, Burial, and Smothering

Effects of drilling effluent deposition should be localized around the discharge site. The degree of effect will depend on the quantity of solids discharged, local conditions around the discharge site, and the biota inhabiting the vicinity of the discharge site.

During offshore drilling operations, discharged drilling fluids and cuttings may accumulate in sediments surrounding the well site. Most of the drilling fluids and cuttings are deposited on the seafloor near the discharge site. The area of seafloor over which this deposition occurs is primarily a function of current velocity and water depth (de Margerie 1989). Ayers et al. (1980) estimated that 90% of the solids from a bulk discharge of drilling fluids are found in the lower plume, which is the part of the discharge that descends immediately to the seafloor. Over time, the lower plume material is transported beyond the initial deposition point near the well site, depending on resuspension by waves and currents (NRC 1983; Boothe and Presley 1985).

In low-energy environments, cuttings piles have been observed. Gillmor et al. (1985) reported observing such piles in water depths of about 120 m at their study site in the Mid-Atlantic area off New Jersey. Cuttings were observed in a zone of approximately 150 m in diameter around the discharge site (Menzie et al. 1980). Continental Shelf Associates, Inc. (1989) observed cuttings and drilling fluids on the bottom near a discharge site located in a water depth of 50 m offshore the Florida Panhandle. Cuttings were seen only within 100 m of the well site. Sediments that appeared to be discharged drilling fluid were observed at the drill site. In higher energy environments, deposition of discharged effluents is much reduced, such as near Tanner Bank, California (Ray and Meek 1980).

Depositional effects on biota vary. Barite and bentonite clays, major components of drilling fluids, are practically inert toxicologically, but they may cause physical damage to organisms through abrasion or clogging (Neff 1987). Sessile benthic organisms may be smothered by rapid accumulation of cuttings near the discharge site (Gettleson 1980).

Thompson et al. (1989) reported the results of monitoring an exploratory well in the Florida Big Bend area. The seagrass *Halophila decipiens* occurred around the discharge site. Complete mortality of the seagrass within 300 m of the discharge site was attributed to smothering by discharged drilling effluents. Recovery was observed within one year after drilling ceased. However, the passage of Hurricane *Elena*, which destroyed much of the deep seagrass beds in the Florida Big Bend, made interpretation of recovery difficult; that is, the degree and rate of recovery from drilling alone could not be determined. As part of the same program, Continental Shelf Associates, Inc. (1988) observed drastic reductions in coverage of a hard bottom community that occurred 25 m from the discharge site. Burial by discharged cuttings was thought to be responsible for this reduction.

Turbidity and Light Reduction

Turbidity and reduced light can be expected to affect the autotrophic components of an ecosystem. In the study area, these include seagrasses, corals (which have symbiotic, photosynthetic zooxanthellae), benthic algae, and phytoplankton. Because photosynthetic autotrophs are the basis of production in most ecosystems, reductions in production can affect higher trophic levels and overall community structure.

Kendall et al. (1985) studied the effects of turbidity on the metabolic state of the staghorn coral (*Acropora cervicornis*), using *in situ* experimental chambers. Corals were exposed for 24 h to turbidity regimes produced by 50 and 100 ppm suspensions of kaolin (clay). The investigators measured calcification rate, protein concentration, and free amino acid (FAA) pool after the 24-h exposure and again after a 48-h recovery period in clean seawater. The no-effect concentration for the calcification rate and FAA pool parameters was between 50 and 100 ppm kaolin. Protein concentrations remained unchanged during both exposure and recovery. Calcification rate returned rapidly to control levels during the recovery period, but the reduced FAA pool was slower to

respond. Turbidity stress produced considerable change in coral metabolism. Turbidity not only decreased photosynthetic activity and the synthesis of small molecules, but also caused a large increase in the utilization of stored organic molecules for metabolically costly processes such as mucus production and sediment removal. Kendall et al. concluded that the metabolic parameters measured may not give a true picture of coral stress and recovery. Complete recovery from turbidity stress may take much longer than indicated by a return to control values for the parameters measured.

Kelly et al. (1987) summarized the results of microcosm experiments on the effects of drilling fluids on turtle grass, *Thalassia testudinum*. The effects of the suspended particulate phase of used drilling fluids (which contained diesel) and montmorillonite clay were examined. Exposures were for 10 d at 200 and 1,000 µL/L and 190 d at 290 µL/L. Results of the montmorillonite clay experiments were mixed, but did indicate that *Thalassia* was physiologically stressed by reduced light conditions, as indicated by changes in chlorophyll per unit weight of *Thalassia*. Comparison of the laboratory results with field populations also indicated responses to decreased light. The microcosm experiments were somewhat unrealistic because continuous exposures probably do not occur in the field.

Thompson et al. (1989) monitored seagrass (*Halophila*) growth around an exploratory well site in the Florida Big Bend area. They observed complete mortality of seagrass within 300 m of the well site, and reductions in numbers of leaves and leaf biomass at stations between 300 and 3,700 m from the discharge site. The reductions beyond 300 m were attributed to increased turbidity levels from continuous, low-volume discharges of fine-grained cuttings and the presence of the seagrass near its lower depth limit (light-limitation boundary). Because only a single reference station was available for comparison, the existence of sublethal effects beyond 300 m could not be demonstrated conclusively from these data.

Modification of Benthic Substrates

Modification of benthic substrates near discharge sites is a potential effect from drilling activities in the study area. The presence of particular substrates is, to a large extent, responsible for the biota present in an area. For example, the presence of sand in an offshore area is a habitat where *Halophila* beds may be found. Hard bottom assemblages depend on the occurrence of appropriate hard substrate. Such was the case in the area around the exploratory well monitored in the Florida Big Bend area by Continental Shelf Associates, Inc. (1988). Neff (1987) suggested that barite and bentonite clays may change substrate type; such changes can inhibit habitation by some biota and enhance conditions for others.

The presence of drilling fluids on and mixed in sediments has been demonstrated, in the laboratory, to affect recruitment of benthic organisms. Rubinstein et al. (1980) found that a layer of drilling fluids at high concentrations reduced the number of polychaete and mollusc species developing from planktonic larvae in flow-through aquaria. Tagatz et al. (1980) studied the effects of drilling fluids on recruitment in microcosms intended to simulate field conditions that may occur when drilling fluid covers a substratum or mixes with ambient sediments. A sand substratum was layered with barite and whole drilling fluids (lignosulfonate type drilling fluid from an active drilling rig offshore Louisiana); mixtures of sand and these components were also prepared. Contaminated and uncontaminated experimental units were exposed for a minimum of seven weeks to unfiltered, flowing seawater, and recruitment was determined. The investigators found that layering of the substrate reduced abundances of annelids, arthropods, cnidarians, and molluscs, depending on the length of the exposure. Mixtures of sediment with drilling fluid and with barite reduced annelid abundance;

sediment/drilling fluid mixtures reduced cnidarian abundance. The experimental units that had drilling fluid or barite layered over the sand substratum also exhibited reduced average numbers of species in comparison with the uncontaminated experimental units.

Gillmor et al. (1985) reviewed the results of monitoring an exploratory drilling effort conducted in the Mid-Atlantic region off New Jersey. They observed increased abundances of hake (primarily *Urophysis chuss*) in the area of accumulated cuttings near the discharge site, up to one year after discharges ceased. The area of cuttings deposition was thought to attract these fish because the accumulations increased the micro-relief of the seafloor. The investigators also observed reduced abundances of galatheid crabs near the discharge site, possibly because of substrate modification or increased predation by bottom fishes such as the hake. EG&G Environmental Consultants (1982) proposed a diminishment-of-recruitment hypothesis to explain reduced densities of organisms near the Mid-Atlantic discharge site after drilling. They postulated that alterations of surficial sediments from deposited drilling effluents may have limited larval recruitment. Reductions of polychaetes outside the area of burial effects after drilling may have been due to this phenomenon. Abundance and size-frequency data supported the hypothesis for the brittle star *Amphioplus macilentus*. However, the authors did not eliminate the possible explanation that brittle stars emigrated from areas heavily influenced by drilling discharges.

Clark and Patrick (1987) examined the effects of used drilling fluids and barite incorporated into sediments on lancelets in a laboratory experiment. Barite and three drilling fluids were mixed with beach sand. In addition to lethal effects in the drilling fluid treatments, the authors observed reduced burrowing in the barite/sediment mixture. These results indicate that the sublethal effects observed for the drilling fluid/sediment mixtures may have been partially due to a change in the particle size of the substrate. The investigators stated that the potential effects would be limited to habitats located close to discharge sites.

Continental Shelf Associates, Inc. et al. (1989) studied the effects of drilling multiple (six) production wells at a shallow-water (24 to 26 m) site off the South Texas coast. The investigators collected samples to evaluate sediment grain size, trace metal concentrations, and hydrocarbon concentrations, including polynuclear aromatic hydrocarbons. They also collected samples for benthic infaunal composition. The study results showed differences between sampling sites located near the outfall and sites located farther away. Hydrocarbon and trace metal concentrations were greater nearer the discharge site. Barium levels appeared to be elevated above expected background concentrations over much of the study area. The composition of the macroinfaunal assemblage was also different near the outfall, but these differences were not well correlated with differences in sediment due to drilling fluids. The presence of rubble produced on the platform structure, e.g., dead mollusc shells, was primarily responsible for the presence of surface-dwelling carnivores and other species absent at sampling sites farther from the discharge site.

Tissue Contamination

Whether organisms accumulate components of discharged drilling effluents is an environmental concern, because sufficient concentrations could be harmful to the organisms. In addition, contaminants could be passed through the food web and accumulated in higher trophic levels.

Neff et al. (1985) examined potential for bioaccumulation and biomagnification of barium and chromium from the settleable portion of used drilling fluids. The study organisms were the sandworm *Neanthes virens*, the ocean scallop *Placopecten*

magellanicus, the clams *Mercenaria mercenaria* and *Mya arenaria*, the winter flounder *Pseudopleuronectes americanus*, the American lobster *Homarus americanus*, and the bay scallop *Argopecten irradians*. Experimental animals were exposed to solid substrate of drilling fluid/sediment mixtures (nominal barium concentrations of 5,000 to 10,000 ppm above background). Exposure duration was up to 119 d. Periodic measurements of sublethal responses and tissue concentrations of barium and chromium were performed. All species except the clam *M. mercenaria* accumulated barium; four species (sandworms, ocean scallops, lobster, and bay scallops) accumulated chromium. After the animals were exposed to clean sediments, barium and chromium levels in tissues rapidly returned to background. Some sublethal effects were observed--alterations in biochemical composition, depletion of micronutrients, and altered rates of respiration and excretion, which indicated mild stress from exposure to settleable fraction. However, the stress was insufficient to significantly decrease growth rate and growth efficiency of juvenile lobsters and flounder.

In a set of related experiments, Neff et al. (1985) fed contaminated prey (sandworms that had accumulated barium and chromium from drilling fluid/sediment mixtures) to lobsters and winter flounder. The experiments continued over a sufficient period for the test organisms to consume several times their body weight. There was no net accumulation of barium and chromium in the lobster or flounder fed the contaminated prey. In addition, in test organisms exposed to contaminated sediments and fed contaminated food, tissue concentrations did not exceed those observed in animals exposed to contaminated sediments alone. These investigators concluded that food chain transfer and biomagnification of barium and chromium from the settleable fraction of drilling fluids did not occur.

Impure barite (barium sulfate) used in drilling fluids is often contaminated by metals such as arsenic, cadmium, chromium, copper, iron, lead, mercury, nickel, and zinc (Kramer et al. 1980; Trefry et al. 1986). The EPA proposes to regulate the concentrations of cadmium and mercury in drilling fluid barite (40 CFR Part 435). In response to concerns raised regarding the bioavailability of some of these trace metals present in impure barite, Neff et al. (1986) used impure barite in an experiment similar to that performed by Neff et al. (1985). The metals of major environmental concern were arsenic, cadmium, copper, lead, and mercury. The investigators combined clean sediments with low-trace-metal barite or high-trace-metal barite to provide a nominal barium concentration of 100,000 ppm over background (a level much higher than concentrations observed in the field). The test animals were juvenile winter flounder *Pseudopleuronectes americanus*, the grass shrimp *Palaemonetes pugio*, the sandworm *Nereis virens*, and the clam *Mya arenaria*. The exposure period was 13 wk, with sampling at 1 and 4 wk. The flounder failed to accumulate any of the trace metals during the 13-wk exposure period. Clams exhibited a tendency to accumulate small amounts of cadmium and lead when exposed to the high-trace-metal barite/sediment mixture and, to a lesser extent, when exposed to the low-trace-metal barite/sediment mixture. Accumulation of cadmium, copper, and lead in sandworm tissues was observed; slight accumulations of lead and mercury were observed for the grass shrimp. Statistical analysis revealed that the concentrations of the metals covaried in the tissues of the clams, sandworms, and shrimp, suggesting that much of the apparent accumulation was due to unassimilated barite particles in the gut or gills. The investigators concluded that metals associated with impure barite were virtually unavailable for bioaccumulation and do not represent a potential hazard in the marine environment.

Continental Shelf Associates, Inc. (1988) studied the effects of exploratory drilling of a well in a seagrass bed (*Halophila decipiens*) in the Florida Big Bend area. As part of their program, they examined bioaccumulation in the seagrass. The seagrass accumulated barium, but not chromium, as a result of drilling discharges. Turkey-wing oysters

(*Arca zebra*) at a site located 25 m from the discharge also accumulated barium; however, these organisms were undepurated, and the barium may have been present in the gut rather than in the tissues.

As part of a monitoring study of exploratory drilling in the Santa Barbara Channel, California, Jenkins et al. (1989) examined the subcellular distributions of barium in four species that had different feeding strategies. These infaunal species were the cardit clam *Cyclocardia ventricosa* (a filter feeder), the ice-cream-cone polychaete *Pectinaria californiensis* (a deposit feeder), and two nephtyid polychaetes, *Nephtys ferruginea* and *N. caecoides* (actively burrowing deposit feeders). The investigators observed significant bioaccumulation in the cardit clam and the ice-cream-cone polychaete. Analysis of the subcellular distributions of barium in these organisms revealed that over 97% of the metal was in the granular fraction; increases in this fraction were due to drilling activities. However, the investigators pointed out that the quantity of granular barium may have been overestimated because these two organisms may have retained some barium in the gut and epithelium. They thought that concentrations of soluble barium were insufficient to disrupt calcium metabolism of the organisms (barium ions could potentially compete with calcium ions for ligands within the cell, if present in sufficient quantities).

Altered Water Temperature, Salinity, and Nutrient Concentrations

Various water quality parameters such as temperature and salinity could be modified by routine discharges. For example, produced water is often a hypersaline brine. The effect of such changes is likely to be restricted to the immediate vicinity of the discharge because dispersion of the discharged material occurs rapidly in open water, similar to the brine discharges observed by Hann et al. (1985). Likewise, discharges of domestic waste may serve as a nutrient source. With proper treatment of these wastes prior to discharge, effects on water quality also would be restricted to immediately near the discharge point.

Potential Effects on South Florida Communities and Resources

Coral Reefs

Coral reefs are an important biological component of the South Florida area. The presence of the reefs makes a major contribution to the unique nature of the Florida Keys (see **Chapter 4**). The corals *per se* serve as important primary producers for the ecosystem, and their intricate, complex framework provides habitat for the multitude of organisms associated with the reefs. The potential effects of routinely discharged materials to corals are an important issue because corals are critical to the reef ecosystem.

Thompson and Bright (1977) examined the ability of three species of corals to clear their surfaces of four types of sediments. These species of hermatypic corals--*Diploria strigosa*, *Montastraea annularis*, and *M. cavernosa*--are common on the outer reefs of the Florida Keys (**Chapter 4**). Slurries of used drilling fluid, barite, bentonite, and calcium carbonate were poured over the test organisms at concentrations potentially observed in the near vicinity of a discharge site. The corals were able to clear their surfaces of barite, bentonite, and calcium carbonate. None of the corals were able to clear themselves of the used whole drilling fluid, a result the investigators attributed to chemical toxicity. Although the results indicated that used whole drilling fluids were toxic to corals, the investigators noted that severe doses, unrepresentatively high relative to expected exposures during actual drilling, were applied.

In their review of the effects of drilling fluids on reef corals, Dodge and Szmant-Froelich (1985) reported the results of other experiments conducted by Thompson. In laboratory experiments, Thompson buried two species of corals in carbonate sand and in a used, whole drilling fluid. He attempted to simulate field conditions expected in the very near vicinity of a discharge. Thompson found that colonies of *Montastraea annularis* and *Porites astreoides* buried in carbonate sand for periods of 8 and 15 h, respectively, recovered from the stress, although zooxanthellae expulsion was observed. Colonies of the two coral species buried similarly in used, whole drilling fluid did not survive. In related field experiments, Thompson found that natural water movements facilitated sediment removal from colonies of *M. annularis*. This result suggested that natural water movements may be important in reducing exposure of corals to detrimental effects of drilling fluids observed in the laboratory.

Hudson et al. (1982) reported reductions up to 90% in coral coverage within 85 to 115 m of a drill site located on a Philippine reef. These investigators postulated that prolonged smothering by discharged cuttings and associated drilling fluids was responsible for the reductions.

Shinn et al. (1989) surveyed seven sites where exploratory drilling had occurred to examine the effects of drilling under tropical/subtropical conditions. Six of the wells (two wells were located at one site) were drilled in shallow water (4.5 to 23 m) near the Marquesas Keys between 1959 and 1962, prior to the enactment of stringent OCS environmental regulations. The wells were located in a variety of environments: bare sand, seagrass and gorgonians, and coral reefs. Two deepwater (53 and 70 m) wells drilled off the West Florida coast in 1981 and 1986 were also surveyed. The investigators concluded that observed effects were due to mechanical damage associated with placement of the drilling rig and discarded materials. Rig footprints, a pad built from pea gravel, discarded cement bags, and iron debris had altered the environments at several sites. At the bare sand site, discarded debris formed an artificial reef populated by corals, fleshy algae, and reef fishes. The investigators found no indication that drilling fluid or cuttings negatively affected the biota in the areas around the well sites. The presence of cuttings was detected by microscopic examination of sediment samples. Chemical analyses of the sediments for drilling fluid tracers (e.g., barium) were not performed. Shinn and colleagues concluded that the effects from exploratory drilling operations could easily be avoided because the observed damage was mechanical. Placement of rigs on sandy bottoms, even near coral reefs, would eliminate damage, provided debris was not discarded from the drilling rig.

Sublethal responses of corals to drilling fluids have been reported by several investigators. White et al. (1985) reported changes in fatty acid metabolism induced by exposure to drilling fluids that contained chromium and No. 2 diesel oil. Thompson and Bright (1980) observed increased polyp retraction in five species of corals (*Acropora cervicornis*, *Agaricia agaricites*, *Montastraea annularis*, *Porites astreoides*, and *P. furcata*) exposed to a laboratory-formulated drilling fluid at concentrations expected near a discharge site ($\geq$0.100 mL/L). Powell, Bright, and their colleagues at Texas A&M University conducted a series of *in situ*, sublethal, drilling fluid exposure experiments on the staghorn coral *A. cervicornis* at Carysfort Reef in the Key Largo National Marine Sanctuary (Kendall et al. 1983). In a series of experiments using an *in situ* experimental chamber, corals were exposed for 24 h to various concentrations of different drilling fluids (25 to 500 ppm). They were then allowed to recover in clean seawater for 48 h. The metabolic state of the corals was determined by measuring the calcification rate, total soluble tissue protein concentration, and FAA pool. Toxicity of the various drilling fluids tested varied considerably. The level of no effect ranged between 5 to 15 ppm for most drilling fluids for 24-h exposures (Powell et al. 1984a). Zooxanthellae loss was observed after 24-h exposure at the 500 ppm level (Kendall et al. 1983),

although such loss probably would have been apparent at lower exposure concentrations had the experiment been extended. The calcification rate was a much more sensitive measure of drilling fluid stress during exposure than were changes in tissue components. However, it rapidly returned to control values during the recovery period, even though the behavior of the other metabolic parameters (e.g., FAA pool) indicated complete coral recovery had not occurred (Kendall et al. 1984). An experiment with equivalent concentrations of kaolin (a clay used to produce turbidity) caused no change in protein concentration and a much lower drop in calcification rate. This suggested that an increase in turbidity alone did not cause the toxic effects observed for drilling fluid. Powell et al. (1984b) concluded that the degree of toxicity of drilling fluid could not be accurately predicted from 24-h exposure data alone.

The best means to minimize effects of drilling discharges on corals is to spatially separate them from the drilling effluent source. Dodge and Szmant-Froelich (1985) pointed out that many of the effects of drilling fluids occur at concentrations of 0.1 mL/L or greater. Such concentrations of drilling fluid would be expected to occur only in the near vicinity of a discharge site in an open-water situation. Cuttings deposition is primarily limited to within 100 m of the discharge site. Burial and significant sedimentation, which could result in smothering of coral reef assemblages, also would be restricted to the near vicinity of a drilling discharge site. Such effects would be reduced or eliminated if the discharge site is located a sufficient distance from the coral assemblage. More subtle effects may occur as the result of reduced light penetrations from increased turbidities. Chronic turbidity would be more likely if drilling generates fine-grained cuttings that are continuously discharged. The environmental consequences of multiple wells from a single site such as during development are not well studied. Rapid dispersion of produced water and domestic wastes should insure that water-quality changes are limited to the near vicinity of the discharge. Discharges in shallow-water areas that have low flushing rates may increase the possibility of effects on coral reef biota.

Shunting (discharging drilling effluents near the seafloor through an extended discharge pipe) is a mitigation measure that has been used to protect corals on the Flower Garden Banks in the northwestern Gulf of Mexico. Because the corals inhabit the crests of banks elevated well above the surrounding seafloor, shunting keeps discharges from nearby drilling operations from reaching the corals. In South Florida, shunting would not be an appropriate mitigation measure, because the reefs are not located on a topographic feature like the Flower Garden Banks.

Seagrass and Benthic Algal Communities

Seagrass and benthic algal communities are important components of the South Florida continental shelf, and seagrass ecosystems are among the richest, most productive coastal ecosystems (**Chapter 4**). Nearshore seagrass beds, such as *Thalassia* meadows, are highly productive, contributing to grazing and detrital food webs. They provide a nursery area for juvenile species and they stabilize the sediment habitat.

In a series of microcosm experiments, the effects of continuous exposure to various concentrations of drilling fluids on a *Thalassia* community were conducted at the EPA Gulf Breeze Laboratory (Morton et al. 1986; Price et al. 1986; Kelly et al. 1987; Morton and Montgomery 1989). Most of these experiments were conducted with a drilling fluid that contained diesel oil, and exposures were continuous for periods of approximately 6 wk. The presence of diesel in drilling fluids has been shown to influence the degree of drilling fluid toxicities observed in laboratory bioassays (Duke and Parrish 1984). The results must be carefully considered because the discharges of diesel-containing drilling fluids are now prohibited by the NPDES permit issued for the Gulf of Mexico

in 1986 (L. Wise, pers. comm. 1990). As discussed earlier, new regulations proposed by the EPA (40 CFR Part 435) also would prohibit discharging drilling fluids and cuttings containing detectable quantities of diesel.

A variety of effects was observed in the seagrass microcosm experiments. Lower growth and productivity of *Thalassia* were observed. Increased chlorophyll *a* per unit biomass indicated physiological adaptation to reduced light levels. Lower decomposition rates of *Thalassia* leaves suggested effects on nutrient recycling and slowed entrance of nourishment into detrital food webs. Abundances of benthic macrofaunal organisms associated with the seagrass beds were reduced in microcosms exposed to the drilling fluid treatments; these changes were thought to be due to ecotoxicological and disturbance-related changes.

In their study of previous exploratory drill sites, Shinn et al. (1989) surveyed a site near the Marquesas Keys where two wells were drilled in 1961 and 1962. A seagrass community (*Thalassia*, *Syringodium*, and *Halodule*) inhabited fine-grained sediments, seemingly unaffected by the previous drilling operations, except for a pile of pea gravel and a pile of hardened cement sacks. This discarded material evidently altered the substrate sufficiently to preclude colonization by seagrasses.

In their study of exploratory drilling in offshore *Halophila decipiens* beds, Thompson et al. (1989) observed smothering of seagrasses within 300 m of the discharge site. They also observed reduced production at greater distances, probably because increased turbidity reduced light levels in an area where the seagrass was living near its lower depth limit. Hurricane *Elena*, which passed over the drill site during the study, disturbed the sediment during the monitoring and stripped the seagrass from the substrate. *Halophila* recolonization was observed during two surveys conducted one and two years after drilling, including the area of complete *Halophila* mortality.

The best means of protecting seagrass beds from drilling discharge effects is to restrict discharges near the beds, particularly climax (*Thalassia*) beds. Discharges near seagrasses would affect the biota in these beds. Smothering and reduced production by the plants from increased turbidity may occur if the distance between the discharges and the beds is insufficient. Ecotoxicological effects would be limited to the near vicinity of the discharge because dispersion occurs rapidly. In areas of poor flushing, the probability of environmental consequences would be greater. Climax *Thalassia* beds would be expected to recover more slowly than offshore beds of the pioneer species *Halophila decipiens*.

Water Column Communities

The effects of routine discharges would be expected to be limited to the near vicinity of the discharge site. Plume observations have indicated that the high mixing rates will rapidly reduce concentrations of potential toxicants to levels below those observed as detrimental in the laboratory. Alldredge et al. (1986) investigated the effects of used drilling fluids at several concentrations (dilutions of 10 to 10^7) and a number of drilling fluid additives on the productivity of natural assemblages of marine phytoplankton in the Santa Barbara Channel (California). Their data indicated that the primary production of natural phytoplankton assemblages would not be reduced by initial exposure to discharged drilling fluids. In addition, these investigators thought that primary production would be unaffected by long-term exposure because drilling fluids are rapidly diluted.

Hay et al. (1988) investigated rates of recruitment, growth, and mortality of enclosed populations of the marine copepods *Pseudocalanus elongatus*, *Acartia clausi*, and *Temora longicornis* exposed to produced water from North Sea oil production platforms. These rates were estimated using a population dynamics model. The effect of the produced water was primarily limited to reducing recruitment over the 87-d exposure period.

Many species are found in the benthos as juveniles and adults and are present in the plankton as larvae. These are called meroplankton, in contrast to holoplankton, which spend their entire life history in the plankton (see **Chapter 6**). Exposure of meroplankton to routine discharges could therefore be detrimental to benthic recruitment. Crawford and Gates (1981) examined the effects of a drilling fluid from Mobile Bay on the development of the sand dollar *Echinarachnius parma*. The drilling fluid was supplied by the EPA and not designed for ocean discharge. These investigators observed normal development of sand dollar plutei (planktonic larval form) at concentrations of drilling fluids up to 100 ppm. They observed abnormal development and reduced fertilization success at concentrations of 1 ppt, which roughly corresponds to concentrations observed near a discharge site.

Fish and Fisheries

The effects of routine discharges on fish and fisheries should be limited. As discussed earlier, rapid dispersion of discharges generally precludes large scale impingement of toxic concentrations of the discharges on biota. However, some effects may occur in the near-field. Gillmor et al. (1985) reported increased abundances of demersal fishes around a cuttings pile in the Mid-Atlantic. The increased fish populations may have resulted in increased predation pressure on galatheid crabs in the near vicinity of the discharge. Other habitat disturbances may affect recruitment of demersal fishes within the near-field of drilling fluid discharges. Crawford and Gates (1981) observed effects on the development of the mummichog *Fundulus heteroclitus* exposed to high concentrations of the Mobile Bay drilling fluid supplied by the EPA. *Fundulus* embryos exposed to 10,000 and 1,000 ppm drilling fluid had a reduced rate of development and heartbeat rate. Hatching success was reduced for concentrations of 100, 1,000, and 100,000 ppm drilling fluid. Sharp et al. (1985) reported the results of experiments on *Fundulus* embryos exposed to a used, medium-density seawater chrome lignosulfonate drilling fluid. This drilling fluid was obtained from an offshore exploratory platform in the Gulf of Mexico. In addition to the major constituents (barite, bentonite clay, chrome lignosulfonate, lignite, and sodium hydroxide), it contained petroleum hydrocarbons (thought to be diesel oil). The bioassay testing was performed using the aqueous fraction of the drilling fluid. Mortalities of embryos increased with increasing concentrations of drilling fluid. In addition, other effects related to increasing concentrations of drilling fluid were increased structural anomalies of the embryos, decreased heart rate, decreased hatching success, delayed hatching, and decreased hatching size. Microcosm experiments performed by Gamble et al. (1987) revealed no direct effects on cod (*Gadus morhua*) and herring (*Clupea harengus*) larvae; rather, reduced growth of larval herring resulted from reduced copepod recruitment.

Among the important invertebrate fisheries in the study area are the pink shrimp *Penaeus duorarum*, the spiny lobster *Panulirus argus*, and the stone crab *Menippe mercenaria* (**Chapter 7**). Spiny lobster and stone crab are largely dependent on hard bottom/coral reef habitats. Habitat alterations due to burial during drilling discharges would effectively remove suitable habitat for these species, at least until physical forces (waves and currents) removed the deposited material and the habitat recovered sufficiently to support these two species. The Tortugas shrimp grounds are an important area for harvesting pink shrimp. Adult shrimp are motile and would be expected to avoid areas of unsuitable substrate. Although drilling has occurred in the northwestern Gulf of Mexico for over 30 years, shrimping remains a major fishery in this region.

Other Offshore Benthic Communities

Several low-relief, hard bottom communities occur in the offshore portion of the South Florida area. Conspicuous groups in these communities are stony corals, octocorals, sponges, and crinoids (**Chapter 5**). Distributions of the communities are primarily determined by (1) geomorphology, which controls sediment thickness and consequently, hard substrate availability; and (2) light, which controls the distributions of autotrophs (photosynthetic primary producers).

Aside from potential toxic effects in the near vicinity of the discharge site, the effects of routine discharges would be related to alteration of the environment with respect to substrate availability and light. Large quantities of sediments are discharged during drilling operations. Because much of this material will probably settle near the discharge site, burial and smothering of the biota may occur in this area. Substrate may be modified, reducing recruitment until natural forces (e.g., storms) move the sediments, exposing the hard substrate. Farther from the discharge site, increased sedimentation may affect sensitive biota such as the reef coral *Agaricia*.

The upper plume of drilling effluent discharges could potentially reduce the quantity of light and alter the quality of light reaching the seafloor. Photosynthetic organisms, such as algae and corals, may be affected by such increased turbidities. The degree to which an autotroph is affected will depend on the duration of increased turbidities, the sensitivity of the autotroph, and the depth at which the autotroph is living (how close to the compensation depth the organism is living). Increased turbidity levels at a particular location removed from the discharge site (>1,000 m) should be infrequent and temporary. If increased turbidities occur for extended periods, higher trophic levels that depend on the autotrophs for nutrition and/or habitat may be affected.

CONCLUSIONS

If further oil and gas operations occur in the South Florida area, a variety of materials will be routinely discharged into OCS waters, given the current regulations. Because this region is a unique subtropical/tropical environment, it is important to evaluate the potential fate and effects of these discharges before operations begin. This evaluation will aid in determining policy for protecting the unique habitats in the region.

Three basic conclusions are apparent from a review of fate and effects of routine discharges for potential oil and gas operations in South Florida:

- Routine discharges could potentially affect the biota of South Florida, particularly at high concentrations near the discharge point. Effects probably would be limited to within a few hundred meters of the discharge site.

- The fate of routine discharges will vary between restricted, poorly flushed and open OCS regions of the shelf. This difference in fate will bear on the effects to the biota, because exposures will differ.

- The best means to minimize effects of routine discharges is to spatially isolate them from sensitive biota.

Under current regulations for the Eastern Gulf of Mexico Planning Area, the area within 1,000 m of a proposed well site must be visually surveyed and photographed (Minerals Management Service 1987). The purpose of this survey is to ascertain whether live bottom (a term that includes hard bottom communities and seagrass beds--see **Chapter 5**) is present. If live bottom is present, special steps may be required to mitigate the effects from the drilling operations. Based on these regulations, sensitive

biota can be protected, if detected within 1,000 m. However, some potential effects, such as increased turbidity, can elicit effects, albeit sublethal, farther from the outfall during exploratory operations. This prescribed distance is probably sufficient for single exploratory wells. In the event that multiple wells are drilled at a single site or the number of wells begins to increase in a sensitive area, the 1,000-m survey zone may be insufficient. Drilling from multiple well production platform sites is poorly studied, and not at all for the sensitive, light-dependent communities that exist in South Florida. Further study is necessary to determine adequate buffers for drilling multiple wells near sensitive biota.

Although laboratory and field studies have been conducted to determine short-term effects from exploratory drilling efforts, few studies of long-term effects and studies of discharges from multiple wells at a single location have been performed. Several studies have been performed in the northwestern Gulf of Mexico in areas of production such as the Offshore Ecology Investigation, the Central Gulf Platform Study, and the Buccaneer Gas and Oil Field Study; however, these have suffered criticism based on their design (Carney 1987). Although much information was collected during these studies, the data were often difficult to interpret because natural variability was high, a common problem with field studies. Experimental designs should be ecologically and statistically sound. This can alleviate many of the problems associated with large natural variability. Preliminary sampling should be conducted to determine proper numbers of replicates; adequate statistical power is important. Statistical testing of specific, clearly defined hypotheses is necessary in long-term studies.

Recovery from drilling operations is another area that needs further study, not only as it relates to sensitive communities in South Florida, but in general. As part of an industry-sponsored monitoring program, Thompson et al. (1989) revisited their study site one and two years after drilling occurred. They observed recovery of *Halophila decipiens* beds that were previously eradicated in the vicinity (300 m) of the discharge site. Unfortunately, their recovery results were confounded by the passage of a hurricane over the study area. Shinn et al. (1989) observed recovery, except for some mechanical damage, at seven sites where exploratory drilling had been conducted in South Florida. Their data from well sites at the Marquesas Keys were collected more than 25 years after drilling occurred and therefore provide no information on recovery over the short-term. Also, recovery data from multiple-well production drilling in South Florida are not available.

One aspect of South Florida communities is the prominence of the photosynthetic components (autotrophs) in the habitat structure. Examples include the following: hermatypic corals in the Reef Tract; *Thalassia* in nearshore, climax, seagrass beds; the reef coral *Agaricia* in deepwater reefs; and macroalgae (e.g., *Anadyomene* and *Halimeda*) in offshore, hard bottom areas. The effects of increased turbidity and corresponding reduction of light penetration to these autotrophic components of the benthic communities need further study, especially with regard to chronic turbidity.

Long-term, far-field dispersion and fate of drilling discharges have received almost no study anywhere on the U.S. OCS. Yet this far-field dispersion process is the mediator of any regional effects from drilling discharges. It should be understood as a basis for management decisions concerning regional petroleum exploration and development activities. Research is needed on the regional fate of drilling discharges. Using barium as a tracer of the dispersion process is a logical starting point. Such research also should yield valuable information into regional sediment resuspension, transport, deposition, and accumulation processes. This information would be relevant to virtually all regional management decisions aimed at mitigating adverse environmental effects from pollutants released into an area by human activities.

The mass and fate of radionuclides in produced waters need further study. While it is likely that the rapid dilution of these waters when discharged precludes significant radionuclide accumulation in ambient biota or sediment, the authors are not aware of any study which investigates this issue and confirms the hypothesis of no accumulation. In such a study, it would be especially important to investigate the accumulation of radium in sediments and biota in areas of extensive oil production on the OCS.

REFERENCES CITED

Abernathy, S. A., ed. 1989. *Drilling and production discharges and oil spills in the marine environment.* Herndon, VA: U.S. Department of the Interior, Minerals Management Service.

Alldredge, A. L., M. Elias, and C. C. Gotschalk. 1986. Effects of drilling muds and mud additives on the primary production of natural assemblages of marine phytoplankton. *Mar. Environ. Res.* 19:157-176.

Armstrong, H. W., K. Fucik, J. W. Anderson, and J. M. Neff. 1979. Effects of oilfield brine effluent on sediments and benthic organisms in Trinity Bay, Texas. *Mar. Environ. Res.* 2:55-69.

Auble, G. T., A. K. Andrews, R. A. Ellison, D. B. Hamilton, R. A. Johnson, J. E. Roelle, and D. R. Marmorek. 1982. *Results of an adaptive environment assessment modeling workshop concerning potential impacts of drilling muds and cuttings on the marine environment.* Fort Collins: U.S. Fish and Wildlife Service.

Ayers, R. C., Jr., T. C. Sauer, Jr., R. P. Meek, and G. Bowers. 1980. An environmental study to assess the effect of drilling fluids on water quality parameters during high rate, high volume discharges to the ocean. In *Proceedings, symposium on research on environmental fate and effects of drilling fluids and cuttings,* 351-381. Washington, DC: Courtesy Associates.

Ayers, R. C., Jr., J. E. O'Reilly, E. Y. Chai, and L. R. LaMotte. 1989. The EPA/API diesel pill monitoring program. In *Drilling wastes,* ed. F. R. Engelhardt, J. P. Ray, and A. H. Gillam, 757-773. New York: Elsevier Applied Science.

Boehm, P. D., J. Brown, and A. G. Requejo. 1989. The fate and partitioning of hydrocarbon additives to drilling muds as determined in laboratory studies. In *Drilling wastes,* ed. F. R. Engelhardt, J. P. Ray, and A. H. Gillam, 545-576. New York: Elsevier Applied Science.

Boesch, D. F., and N. N. Rabalais, ed. 1989. *Produced waters in sensitive coastal habitats: An analysis of impacts, central coastal Gulf of Mexico.* OCS Report/MMS 89-0031. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Boothe, P. N., and W. D. James. 1985. Neutron activation analysis of barium in marine sediments from the north central Gulf of Mexico. *J. Trace and Microprobe Techniques* 3:377-399.

Boothe, P. N., and B. J. Presley. 1985. *Distribution and behavior of drilling fluids and cuttings around Gulf of Mexico drilling sites.* Washington, DC: American Petroleum Institute.

Breteler, R. J., P. D. Boehm, J. M. Neff, and A. G. Requejo. 1985. *Acute toxicity of drilling muds containing hydrocarbon additives and their fate and partitioning among liquid, suspended and solid phases.* Washington, DC: American Petroleum Institute.

Brooks, J. M., B. B. Bernard, and W. M. Sackett. 1977. Input of low-molecular-weight hydrocarbons from petroleum operations into the Gulf of Mexico. In *Fate and effects of petroleum hydrocarbons in marine organisms and ecosystems,* ed. D. A. Wolfe, 373-384. New York: Pergamon Press.

Carney, R. S. 1987. A review of study designs for the detection of long-term environmental effects of offshore petroleum activities. In *Long-term environmental effects of offshore oil and gas development,* ed. D. F. Boesch and N. N. Rabalais, 651-696. New York: Elsevier Applied Science.

Clark, J. R., and J. M. Patrick, Jr. 1987. Toxicity of sediment-incorporated drilling fluids. *Mar. Pollut. Bull.* 18:600-603.

Collins, A. G. 1975. *Geochemistry of oilfield waters.* New York: Elsevier Scientific.

Continental Shelf Associates, Inc. 1988. *Monitoring of drillsite A in the Gainesville Area Block 707.* Report submitted to Sohio Petroleum Company. Houston.

Continental Shelf Associates, Inc. 1989. *Pre-drilling and post-drilling surveys for Pensacola Area Block 996.* Report submitted to Texaco Producing Inc. New Orleans.

Continental Shelf Associates, Inc., Barry A. Vittor & Associates, and Geochemical and Environmental Research Group. 1989. *Fate and effects of drilling fluid and cutting discharges in shallow, nearshore waters.* Washington, DC: American Petroleum Institute.

Crawford, R. B., and J. D. Gates. 1981. Effects of a drilling fluid on the development of a teleost and an echinoderm. *Bull. Environ. Contam. Toxicol.* 26:207-212.

de Margerie, S. 1989. Modelling drill cuttings discharges. In *Drilling wastes,* ed. F. R. Engelhardt, J. P. Ray, and A. H. Gillam, 627-645. New York: Elsevier Applied Science.

Derby, J. G. S., and J. M. Capuzzo. 1985. Physiological and behavioral effects of drilling fluid on marine crustaceans. In *Wastes in the ocean, Vol. 4, Energy wastes in the ocean,* ed. I. W. Duedall, D. R. Kester, P. K. Park, and B. H. Ketchum, 289-305. New York: Wiley-Interscience.

Dodge, R. E., and A. Szmant-Froelich. 1985. Effects of drilling fluids on reef corals: A review. In *Wastes in the ocean, Vol. 4, Energy wastes in the ocean,* ed. I. W. Duedall, D. R. Kester, P. K. Park, and B. H. Ketchum, 341-361. New York: Wiley-Interscience.

Duke, T. W., and P. R. Parrish. 1984. *Results of the drilling fluids research program sponsored by the Gulf Breeze Environmental Research Laboratory, 1976-1984, and their application to hazard assessment.* EPA-600/4-84-055. Gulf Breeze, FL: U.S. Environmental Protection Agency.

EG&G Environmental Consultants. 1982. *A study of environmental effects of exploratory drilling on the Mid-Atlantic outer continental shelf: Final report of the Block 684 monitoring program.* Report to the Offshore Operators Committee. New Orleans.

Engelhardt, F. R., J. P. Ray, and A. H. Gillam, ed. 1989. *Drilling wastes.* New York: Elsevier Applied Science.

Enos, P., and R. D. Perkins. 1977. *Quaternary sedimentation in South Florida.* Geol. Soc. Am. Mem. No. 147.

Gallaway, B. J. 1981. *An ecosystem analysis of oil and gas development on the Texas-Louisiana continental shelf.* FWS/OBS-81/27. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Gamble, J. C., J. M. Davies, S. J. Hay, and F. K. Dow. 1987. Mesocosm experiments on the effects of produced water discharges from offshore oil platforms in the northern North Sea. *Sarsia* 72:383-385.

Gettleson, D. A. 1980. Effects of oil and gas drilling operations on the marine environment. In *Marine environmental pollution, 1. Hydrocarbons*, ed. R. A. Geyer, 371-411. New York: Elsevier Scientific.

Gillmor, R. B., C. A. Menzie, G. M. Mariani, and D. R. Levin. 1985. Effects of exploratory-drilling discharges on the benthos. In *Wastes in the ocean, Vol. 4, Energy wastes in the ocean*, ed. I. W. Duedall, D. R. Kester, P. K. Park, and B. H. Ketchum, 243-270. New York: Wiley-Interscience.

Hann, R. W., Jr., C. P. Giammona, and R. E. Randall. 1985. *Offshore oceanographic and environmental monitoring services for the Strategic Petroleum Reserve: Annual report for the West Hackberry site from November 1983 through November 1984.* Report prepared for the U.S. Department of Energy. Washington, DC.

Hay, S. J., G. T. Evans, and J. C. Gamble. 1988. Birth, growth and death rates for enclosed populations of calanoid copepods. *J. Plankton Res.* 10:431-454.

Hudson, J. H., E. A. Shinn, and D. M. Robbin. 1982. Effects of offshore oil drilling on Philippine reef corals. *Bull. Mar. Sci.* 32:890-908.

Imco Services. 1978. *Applied mud technology*. Houston.

Jenkins, K. D., S. Howe, B. M. Sanders, and C. Norwood. 1989. Sediment deposition, biological accumulation and subcellular distribution of barium following the drilling of an exploratory well. In *Drilling wastes*, ed. F. R. Engelhardt, J. P. Ray, and A. H. Gillam, 587-608. New York: Elsevier Applied Science.

Kelly, J. R., T. W. Duke, M. A. Harwell, and C. C. Harwell. 1987. An ecosystem perspective on potential impacts of drilling fluid discharges on seagrasses. *Environ. Manage.* 11:537-562.

Kendall, J. J., Jr., E. N. Powell, S. J. Connor, and T. J. Bright. 1983. The effects of drilling fluids (muds) and turbidity on the growth and metabolic state of the coral *Acropora cervicornis*, with comments on methods of normalization for coral data. *Bull. Mar. Sci.* 33:336-352.

Kendall, J. J., Jr., E. N. Powell, S. J. Connor, T. J. Bright, and C. E. Zastrow. 1984. The importance of monitoring metabolic recovery in the coral *Acropora cervicornis* after short-term exposure to drilling muds: calcification rate and protein concentration. *Coral Reefs* 2:215-225.

Kendall, J J., Jr., E. N. Powell, S. J. Connor, T. J. Bright, and C. E. Zastrow. 1985. Effects of turbidity on calcification rate, protein concentration and free amino acid pool of the coral *Acropora cervicornis*. *Mar. Biol.* 87:33-46.

Kraemer, T. F., and D. F. Reid. 1984. The occurrence and behavior of radium in saline formation waters of the U.S. Gulf coast region. *Isotope Geosci.* 2:153-174.

Kramer, J. R., H. D. Grundy, and L. G. Hammer. 1980. Occurrence and solubility of trace metals in barite for ocean drilling operations. In *Proceedings, symposium on research on environmental fate and effects of drilling fluids and cuttings*, 789-798. Washington, DC: Courtesy Associates.

Menzie, C. A., D. Maurer, and W. A. Leathem. 1980. An environmental monitoring study to assess the impact of drilling discharges in the Mid-Atlantic. IV. The effects of drilling discharges on the benthic community. In *Proceedings, symposium on research on environmental fate and effects of drilling fluids and cuttings*, 499-540. Washington, DC: Courtesy Associates.

Minerals Management Service. 1987. *Final environmental impact statement, proposed oil and gas lease sales 113/115/116, Gulf of Mexico region.* OCS EIS MMS 87-0077. New Orleans.

Morton, R. D., and S. O. Montgomery. 1989. Microcosm studies on the effects of drilling fluids on seagrass communities. In *Drilling wastes*, ed. F. R. Engelhardt, J. P. Ray, and A. H. Gillam, 609-626. New York: Elsevier Applied Science.

Morton, R. D., T. W. Duke, J.M. Macauley, J. R. Clark, A. W. Price, S. J. Hendricks, S. L. Owsley-Montgomery, and G. R. Plaia. 1986. Impact of drilling fluids on seagrasses: An experimental approach. In *Community toxicity testing*, ed. J. Cairns, 199-212. Philadelphia: American Society for Testing and Materials. ASTM STP 920.

National Research Council. 1983. *Drilling discharges in the marine environment*. Washington, DC: National Academy Press.

Neff, J. M. 1987. Biological effects of drilling fluids, drill cuttings and produced waters. In *Long-term environmental effects of offshore oil and gas development*, ed. D. F. Boesch and N. N. Rabalais, 469-538. New York: Elsevier Applied Science.

Neff, J. M., R. J. Breteler, F. I. Saksa, and R. S. Carr. 1985. *Chronic effects of drilling fluids discharged to the marine environment, with emphasis on bioaccumulation/ biomagnification potential of drilling fluid metals.* Washington, DC: American Petroleum Institute.

Neff, J. M., R. E. Hillman, B. Leczynski, and T. Berner. 1986. *Bioavailability of trace metals from barite to benthic marine animals.* Report submitted to the Offshore Operators Committee. New Orleans.

Neff, J. M., R. J. Breteler, and R. S. Carr. 1989a. Bioaccumulation, food chain transfer, and biological effects of barium and chromium from drilling muds by flounder, *Pseudopleuronectes americanus*, and lobster, *Homarus americanus*. In *Drilling wastes*, ed. F. R. Engelhardt, J. P. Ray, and A. H. Gillam, 439-459. New York: Elsevier Applied Science.

Neff, J. M., T. C. Sauer, and N. Maciolek. 1989b. *Fate and effects of produced water discharges in nearshore marine waters.* Washington, DC: American Petroleum Institute.

Payne, J. R., C. R. Phillips, and W. Horn. 1987. Transport and transformations: Water column processes. In *Long-term environmental effects of offshore oil and gas development*, ed. D. F. Boesch and N. N. Rabalais, 175-231. New York: Elsevier Applied Science.

Petrazzuolo, G. 1983. *Draft final technical report document. Environmental assessment: Drilling fluids and cuttings release onto the OCS.* Washington, DC: U.S. Environmental Protection Agency.

Powell, E. N., J. J. Kendall, Jr., S. J. Connor, C. E. Zastrow, and T. J. Bright. 1984a. Effect of eight outer continental shelf drilling muds on the calcification rate and free amino acid pool of the coral *Acropora cervicornis*. *Bull. Environ. Contam. Toxicol.* 33:362-372.

Powell, E. N., S. J. Connor, J. J. Kendall, Jr., C. E. Zastrow, and T. J. Bright. 1984b. Recovery by the coral *Acropora cervicornis* after drilling mud exposure. The free amino acid pool. *Arch. Environ. Contam. Toxicol.* 13:243-258.

Price, A. W., J. M. Macauley, and J. R. Clark. 1986. Effects of drilling fluid on *Thalassia testudinum* and its epiphytic algae. *Exp. Environ. Bot.* 26:321-330.

Rao, K. R., P. J. Conklin, and D. G. Doughtie. 1985. Physiological and histopathological evaluation of the toxicity of hexavalent chromium to the grass shrimp *Palaemonetes pugio* Holthuis. In *Marine pollution and physiology: Recent advances*, ed. F. J. Vernberg, F. P. Thurberg, A. Calabrese, and W. Vernberg, 199-227. Columbia: Univ. of South Carolina Press.

Ray, J. P., and R. P. Meek. 1980. Water column characterization of drilling fluids dispersion from an offshore exploratory well on Tanner Bank, 223-252. In *Proceedings, symposium on research on environmental fate and effects of drilling fluids and cuttings*, 223-252. Washington, DC: Courtesy Associates.

Rose, C. D., and J. T. Ward. 1981. Acute toxicity and aquatic hazard associated with discharged formation water. In *Environmental effects of offshore oil production, the Buccaneer gas and oil field study*, ed. B. S. Middleditch, 301-328. New York: Plenum Press.

Rubinstein, H. I., R. Rigby, and C. N. D'Asaro. 1980. Acute and sublethal effects of whole used drilling fluids on representative estuarine organisms. In *Proceedings, symposium on research on environmental fate and effects of drilling fluids and cuttings*, 828-846. Washington, DC: Courtesy Associates.

Sharp, J. R., R. S. Carr, and J. M. Neff. 1985. Influence of chrome lignosulfonate drilling fluid on the fish, *Fundulus heteroclitus*. In *Wastes in the ocean, Vol. 4, Energy wastes in the ocean*, ed. I. W. Duedall, D. R. Kester, P. K. Park, and B. H. Ketchum, 307-322. New York: Wiley-Interscience.

Shinn, E. A. 1988. The geology of the Florida Keys. *Oceanus* 31(1):46-53.

Shinn, E. A., P. A. Dustan, and B. H. Lidz. 1989. *Biological assessment of the impact of exploratory wells drilled offshore South Florida*. OCS Study MMS 89-0022. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Tagatz, M. E., J. M. Ivey, H. K. Lehman, M. Tobia, and J. L. Oglesby. 1980. Effects of drilling fluids on development of experimental estuarine macrobenthic communities. In *Proceedings, symposium on research on environmental fate and effects of drilling fluids and cuttings*, 847-865. Washington, DC: Courtesy Associates.

Thompson, J. H., and T. J. Bright. 1977. Effects of drill mud on sediment clearing rates of certain hermatypic corals. In *Proceedings, 1977 Oil Spill Conference*, 495-498. Washington, DC: American Petroleum Institute.

Thompson, J. H., and T. J. Bright. 1980. Effects of an offshore drilling fluid on selected corals. In *Proceedings, symposium on research on environmental fate and effects of drilling fluids and cuttings*, 1044-1078. Washington, DC: Courtesy Associates.

Thompson, M. J., A. D. Hart, and C. W. Kerlin. 1989. Exposure of deep seagrass beds off the west coast of Florida to discharged drilling effluents. In *Drilling wastes*, ed. F. R. Engelhardt, J. P. Ray, and A. H. Gillam, 137-156. New York: Elsevier Applied Science.

Trefry, J. H., R. P. Trocine, S. Metz, and M. A. Sisler. 1986. *Forms, reactivity and availability of trace metals in barite*. Report to the Offshore Operators Committee. New Orleans.

U.S. Environmental Protection Agency. 1985. *Assessment of environmental fate and effects of discharges from offshore oil and gas operations*. EPA 440/4-85/002. Washington, DC: U.S. Environmental Protection Agency, Monitoring and Data Support Division, Office of Water Regulations and Standards.

White, D. C., J. S. Nickels, M. J. Gehron, J. H. Parker, and R. F. Martz. 1985. Coral metabolic activity, nutritional status, and microbial infection with exposure to drilling fluids. In *Wastes in the ocean, Vol. 4, Energy wastes in the ocean*, ed. I. W. Duedall, D. R. Kester, P. K. Park, and B. H. Ketchum, 365-376. New York: Wiley-Interscience.

CHAPTER 14
TOXIC EFFECTS OF OIL AND CHEMICALLY DISPERSED OIL ON MARINE ANIMALS AND PLANTS

Edward S. Gilfillan

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INTRODUCTION

The purpose of this review is to give an overview of toxic effects of oil on marine animals and plants, with emphasis on subtropical and tropical species. In producing this review, prior reviews (Engelhardt 1985; Leighton et al. 1985; National Research Council [NRC] 1985, 1989; Rice 1985; Wells and Pearcy 1985; Peakall et al. 1987; Geraci and St. Aubin 1988) as well as many sources of "gray" literature have been consulted. This is not intended to be an exhaustive review. It is meant to give examples of the types of

effects oil may have and the exposure required to produce them. Those studies in which oil exposure is not quantitatively defined will not be considered. In those instances where it is stated that there is no information on oil effects on South Florida species, these statements are based on an extensive search of the open and "gray" literature.

The toxicological effects of oil are dependent on the chemical composition of the oil in question. It is widely appreciated that there are hundreds of different crude oils, which vary tremendously in their composition and hence in their toxicological properties (Pulich et al. 1974; Byrne and Calder 1977; Batterton et al. 1978). It is less widely appreciated that there are also great variations in the chemical composition of refined products (Winters et al. 1977; Batterton et al. 1978).

The toxicity of hydrocarbon compounds is directly related to their solubility in water (Hutchinson et al. 1979). Among the most soluble petroleum hydrocarbons are the low-molecular-weight (LMW), polynuclear aromatic hydrocarbons (PAHs). The LMW PAHs are also responsible for acute toxicity of petroleum hydrocarbons (Anderson et al. 1974; Neff et al. 1976). Anderson et al. (1987) has shown that the toxicity of Prudhoe Bay crude is almost entirely resident in the one-, two-, and three-ring PAHs.

The chemical composition of an aqueous oil solution will change fairly rapidly through evaporation and biodegradation. Both processes will affect the concentration of LMW PAHs most rapidly. This is especially true of chemically dispersed oil (Page et al. 1985a). As a result, it is important to know the changes in concentration and chemical composition that have occurred during experimental exposures.

The toxicological effect that a given oil may have is a function of its chemical composition, the amount applied, and the method and duration of exposure (Byrne and Calder 1977; Anderson et al. 1987). Other sources of stress (e.g., temperature, salinity, oxygen concentration, and parasitism) are also important in determining the effects of a given oil exposure (Laughlin et al. 1978; Linden et al. 1979; Laughlin and Neff 1980; Moles 1980).

Methods used to quantify the amount and composition of oil may give widely different results. Quantification by non-specific methods such as infrared absorption, ultraviolet absorption, fluorescence, or gravimetric analysis yield no information concerning the composition of the oil in question. Much useful information can be obtained from gas-liquid chromatography analysis; even more can be obtained from gas chromatography/mass spectrometry analysis.

The information presented here has varying applicability to predicting oil effects in the real world. Investigations of oil effects typically pass through a number of stages: (1) laboratory lethality studies, which are most useful in comparing relative resistance of various species or in comparing relative toxicity of products; (2) laboratory studies of sublethal effects carried out at unrealistically high exposure levels to induce immediate effects; (3) long-term laboratory studies carried out at low exposures; (4) mesocosm experiments; and (5) field experiments carried out at realistic exposure levels. Field experiments are most useful in predicting field effects; laboratory lethality studies are least useful.

When extrapolating to field situations, it is important to consider that concentrations measured under slicks of non-dispersed oil in the field rarely exceed 250 ppb. In normally dispersive conditions, concentrations of chemically dispersed oil rarely exceed 10 ppm and are rapidly reduced through mixing. As mixing decreases, as in areas with sluggish circulation and some nearshore areas, concentrations of dispersed and non-dispersed oil will be reduced more slowly.

Field experiments are designed to simulate a particular exposure scenario. Their results are most useful in predicting effects of field exposures similar to the scenario used to design the experiment. For example, Ballou et al. (1987) reported that field exposure of corals to about 50 ppm of chemically dispersed Prudhoe Bay crude for 24 h resulted in severe mortality and delayed recovery; Knap (1987) reported that exposure of coral to 10 to 50 ppm of chemically dispersed Arabian Light crude in the laboratory for 24 h followed by field recovery resulted in no damage to corals. It would be wrong to assume that these studies refute one another. Apart from differences in oils and coral species used, these experiments are based on completely different exposure scenarios. Knap's studies simulated one-time dispersion of a slick in a relatively dispersive situation; Ballou's study simulated continuous dispersion over 24 h of a slick in an area with sluggish circulation. They can each be used to predict field experience in appropriate situations (oil type, scenario, circulation regime, and species of coral).

Similarly, it is wrong to say that results of various field experiments are invalid because they did not predict results of the Panama oil spill (Jackson et al. 1989). The Panama oil spill involved much higher exposures (more oil, shallower water, longer exposure times) than any field experiments thus far conducted.

A potential problem is that many studies reviewed here have not used subtropical or tropical species. However, careful examination of toxicological information on arctic, temperate, and tropical species reveals that while there is great variability in resistance of individual species to oil, there are no overall trends. There is no evidence that subtropical and tropical species are more sensitive to oil than temperate or arctic species (Wells and Percy 1985).

The following review has been organized along taxonomic and ecological lines, starting with macroflora, proceeding through plankton, and continuing through invertebrates and vertebrates.

MACROFLORA

Macroalgae

The literature concerning oil effects on macroalgae is sparse. Steele (1977) compared the effects of exposure to light refined oils (No. 2 fuel oil; JP-4; JP-5) and Willamar crude on growth in *Fucus edentatus* embryos over a 12-d period. He found that the refined oils were more toxic than the crude oil; 1 to 3 ppm refined oil arrested growth, whereas 45 to 50 ppm Willamar crude was required to arrest growth.

Bokn (1985) reported results of a two-year exposure study in which effects of chronic exposure to the water-soluble fraction (WSF) of diesel oil (100 ppb; 25 ppb) on growth in *Ascophyllum nodosum* and *Laminaria digitata* were compared. In the first year of the study, no effects of oil on growth in either species were observed. In the second year, growth was significantly reduced by oil treatment in both species. No difference in effects between the two oil exposure levels was detected.

Field observations of the effects of oil on growth in *Laminaria digitata* and *Chondrus crispus* were made following the *Amoco Cadiz* oil spill (Kaas 1981). A slight delay (1 month) in growth of *L. digitata* was observed; no subsequent effects on growth were observed. No effects on growth in *C. crispus* were observed.

Topinka and Tucker (1981) showed that growth of tagged *Ascophyllum nodosum* plants in a location heavily oiled by the *Amoco Cadiz* oil spill fell into normal ranges. The availability of plant nutrients (nitrogen and phosphorus) was much more important for growth than the degree of oiling.

- Conclusions. Based on the results reviewed above, adverse effects of oil on macroalgae can only be expected in areas with very sluggish circulation.

Seagrasses

Considerable literature is available concerning oil effects on temperate grasses such as the eelgrass *Zostera marina* and the smooth cordgrass *Spartina alterniflora*. This information will not be discussed, in view of the fact that there is much information concerning native seagrass species.

Using static bioassays, Baca and Getter (1982) determined the toxicity of oil (Prudhoe Bay crude) and chemically dispersed (Corexit 9527) oil to the turtle grass *Thalassia testudinum*. The toxicity of the WSF of oil was much greater (96-h LC_{50} = 3.8 ppm) than the toxicity of chemically dispersed oil (96-h LC_{50} = 202 ppm). The toxicity of chemically dispersed oil was not very different from the toxicity of Corexit 9527 alone (96-h LC_{50} = 200 ppm).

Using static 100-h bioassays, Thorhaug and Marcus (1985, 1987a,b,c) and Thorhaug et al. (1986) studied toxicity of Murban crude, South Louisiana crude, and seven dispersants to *Thalassia testudinum*, the shoal grass *Halodule wrightii*, and the manatee grass *Syringodium filiforme*. Only slight differences in toxicity were noted between Murban crude and South Louisiana crude. More deleterious effects were observed in plants exposed to dispersed oil than in plants exposed to the WSF. However, high levels of chemically dispersed oil were required to significantly reduce growth. Growth of *T. testudinum* was significantly reduced by 100-h exposure to 1,250 ppm (nominal); growth of *H. wrightii* and *S. filiforme* was significantly reduced by 100-h exposure to 750 ppm (nominal). The nominal concentrations may not represent actual exposures. Measurement of hydrocarbon concentration in a nominal 1,250 ppm exposure yielded 429 ppm; in a nominal 5,000 ppm exposure, the measured concentration was 634 ppm. By contrast, concentrations of total hydrocarbons in the WSF ranged from 5.6 to 10.4 ppm. Toxicity varied widely among the seven dispersants tested. *Thalassia testudinum* was considerably more resistant to dispersant toxicity than *H. wrightii* and *S. filiforme*.

- Conclusions. The seagrasses tested seem to be very resistant to chemically dispersed oil. Adverse effects of field exposure are to be expected only in areas with extremely sluggish circulation.

Mangroves

Mangrove trees are very vulnerable to injury and death resulting from exposure to oil. A number of experiments have been carried out using a variety of mangrove species.

Hannan and Phillips (1975) examined the toxicity of South Louisiana crude, Kuwait crude, No. 2 fuel oil, and No. 6 fuel oil to seeds and seedlings of the black mangrove *Avicennia germinans*. Exposure to >400 mL/m^2 No. 2 fuel oil reduced seed growth; exposure to >800 mL/m^2 killed two-thirds of the seeds. Seedlings were less resistant; exposure to 300 mL/m^2 No. 2 fuel oil killed all seedlings. Exposure to 300 mL/m^2 Kuwait crude caused no mortality in seedlings; the same exposure to South Louisiana crude and No. 6 fuel oil killed 20 and 23% of seedlings, respectively.

Mathias (1977) studied laboratory effects of "diesel oil" on growth of 15 cm *Avicennia intermedia* seedlings from Malaysia. Length of exposure (6 or 12 d) had no effect on growth or survival over 2.5 months. Growth and survival were affected by the degree of oil exposure. At concentrations <10,000 ppm (nominal), growth irregularities were observed; above 10,000 ppm, mortality ensued.

Getter and Baca (1984) studied toxicity of whole and dispersed (Corexit 9527) Arabian Light crude, No. 2 fuel oil, and No. 6 fuel oil to red mangrove *Rhizophora mangle* and black mangrove *Avicennia germinans* seedlings in the laboratory. When oil and oil/dispersant mixtures were injected into the root zone, *A. germinans* was less resistant than *R. mangle*. In *R. mangle*, 50,000 ppm Arabian Light crude and No. 6 fuel oil had no effect on foliage development or stem growth. In *A. germinans*, the same doses of Arabian Light crude and No. 6 fuel oil reduced foliage development and stem growth by 50%. Using No. 2 fuel oil, 50,000 ppm reduced foliage development and stem growth by 50% in *R. mangle*; 5,000 ppm reduced foliage development and stem growth in *A. germinans* by 50%. These results are comparable to those of Mathias (1977) who reported effects on growth in *A. intermedia* at <10,000 ppm "diesel oil." Results obtained by Getter and Baca (1984) with dispersed oils were variable. However, given the differing behavior of dispersed and non-dispersed oils in the environment, injection of dispersed oil into the root zone is not a reasonable scenario; dispersed oil results will not be discussed.

Lai and Feng (1985) investigated the toxicity of dispersed (Corexit 9527) and non-dispersed Arabian Light crude, Malaysian crude, and No. 6 fuel oil to *Rhizophora* (species not given) and *Avicennia* (species not given) in field and laboratory studies. Oil treatments were applied to the sediment surface; a tidal regime was simulated. No. 6 fuel oil was found to be least toxic and Malaysian crude was found to be most toxic. Toxicity of Arabian Light crude to both species was similar (30-d LC_{50} = 300 mL/m^2). Dispersed oil was considerably less toxic than non-dispersed oil; *Avicennia* was slightly less resistant (30-d LC_{50} = 1,716 mL/m^2) than *Rhizophora* (30-d LC_{50} = 2,250 mL/m^2). When the doses reported by Getter and Baca (1984) are calculated in terms of oil applied per square meter, doses required to reduce foliage development and stem growth range from 140 to 1,400 mL/m^2.

A number of investigators have compared the toxicity of dispersed and non-dispersed oil in field experiments (Getter and Ballou 1985; Ballou et al. 1987; Teas et al. 1987). In each instance, effects observed in those trees exposed to non-dispersed oil were more severe than those observed in trees exposed to dispersed oil.

Clearly, the initial composition of oil affects toxicity (Hannan and Phillips 1975; Lai and Feng 1985). The amount of weathering that an oil has undergone is also important in determining toxicity in the field (Page et al. 1985b). Those oils that are richest in low molecular weight aromatic compounds are most toxic.

Soil conditions are also important in determining effects of spilled oil. Dicks (1986) reported that *Avicennia marina* trees living in well-drained sandy soil were less harmed by oiling than trees living in muddy, waterlogged soils.

- Conclusions. *Avicennia* species may be somewhat less resistant to oil effects than *Rhizophora* species. Both genera are readily killed by oil concentrations of 100 to 1,000 mL/m^2, which are likely to occur in actual oil spill situations. Both genera are much more resistant to oil that has been dispersed prior to entering the forest than to undispersed oil.

PLANKTON

Phytoplankton

The literature on the effects of crude oil on the survival, photosynthesis, and growth of phytoplankton is not extensive. This is particularly true when one excludes older work in which oil/dispersed oil concentrations are reported as the amount added (nominal concentration).

Considerable differences have been found in tolerance to petroleum among species of phytoplankton. Pulich et al. (1974) tested seven phytoplankton species against the water-soluble fraction of No. 2 fuel oil and found that they could tolerate 750 ppb to 3.75 ppm total solubles without measurable effect on growth (doubling time). Pulich et al. also concluded that the diatoms they used were more susceptible than flagellates to oil effects. Batterton et al. (1978) studied effects of petroleum on growth in five algal species and found that the green alga *Chlorella autrophica* was considerably more sensitive than either the blue-green alga *Agmenellum quadruplicatum* or diatom *Cylindrotheca* sp. Mahoney and Haskin (1980) found that the diatom *Skeletonema costatum* was more sensitive (EC_{50} for growth = 0.5 to 1.0 ppm) than a number of green flagellates (EC_{50} for growth = 5 ppm) to seawater extracts of Nigerian crude. However, three different clones of *S. costatum* showed markedly different EC_{50}s for growth (0.5, 1.0, 1.5 ppm).

Crude oils have been found to be less phytotoxic than light refined products such as No. 2 fuel oil (Pulich et al. 1974; Batterton et al. 1978). With the oils tested, the differences in phytotoxicity between crude oils and No. 2 fuel oils were on the order of two- to three-fold. The increase in phytotoxicity of the No. 2 fuel oils was ascribed to their higher content of light aromatic hydrocarbons.

Batterton et al. (1978) compared the phytotoxicity of the WSF from five different No. 2 fuel oils. One was innocuous; others were very toxic. Differences in toxicity were ascribed to differences in chemical composition of the WSF. The presence of *p*-toluidine in the WSF was correlated with increased phytotoxicity. As little as 50 ppb *p*-toluidine arrested growth in *Agmenellum quadruplicatum*.

Trudel (1978) exposed natural populations of microflagellates to Venezuelan Lago Medio crude. Photosynthesis was inhibited 10% by 0.1 mg/L (100 ppb) and by 50% at 1 to 2 mg/L (1 to 2 ppm).

Vargo et al. (1982) found that biweekly additions of 100 to 200 µg/L (100 to 200 ppb) of No. 2 fuel oil increased both standing stock and diversity of natural populations of phytoplankton. Increased standing stock and diversity were ascribed to decreased predation by filter-feeding animals.

In a similar experiment, Scholten and Kuiper (1987) found comparable results. They also found that, in times of silicate limitation, diatoms could be replaced by flagellates following oil addition to the microcosm.

Tokuda (1979) concluded from the effects of a number of oils and dispersants on growth in *Skeletonema costatum* that there was no difference between the toxicity of undispersed oil and dispersed oil. Trudel (1978) studied effects of exposure to Lago Medio crude alone and dispersed with Corexit 9527 on carbon-14 uptake of natural populations of phytoplankton. No difference was observed between oil alone and chemically dispersed oil.

- Conclusions. Relatively high levels of dissolved petroleum hydrocarbons are required to adversely affect growth and photosynthesis in marine phytoplankton. Levels measured under and near oil slicks should have little or no effect on primary productivity. Concentrations of oil measured under and near slicks of chemically dispersed oil could adversely affect phytoplankton populations for a short time until natural dilution occurs. However, because of the high growth rates of phytoplankton, any losses will be quickly recovered.

Zooplankton

There is more literature concerning oil effects on zooplankton than for phytoplankton. However, many of the older studies refer to nominal exposure levels and will not be considered in this discussion. Since zooplankton comprise many taxonomic groups, the following discussion will be organized by taxonomic group.

Protozoa

Lanier and Light (1978) showed that the 90-h LC_{50} for *Euplotes diadaleos* exposed to the WSF of Empire Mix crude was 1.7 ppm. Rogerson and Berger (1981) showed that concentrations >1 ppm of Corexit 9527 were acutely toxic to *Tetrahymena pyriformis* and *Colpidium campylum*, but these ciliates grew better in oil/dispersant mixtures than in oil alone. The authors attribute this difference to the enhanced volatilization of the more toxic light aromatics from the oil/dispersant mixtures.

Ctenophores

In a series of experiments (Lee 1975; Lee and Anderson 1977; Lee and Takahashi 1977), *Pleurobrachia pileus* was shown to have a 1-d LC_{50} of 0.59 ppm for the WSF of No. 2 fuel oil (0.14 ppm naphthalenes). No information about effects of chemically dispersed oil on ctenophores is available.

Molluscs

Byrne and Calder (1977) investigated toxicity of the WSF of crude and refined oils to embryos and larvae of the clam *Mercenaria mercenaria*. For embryos, 2-d LC_{50} values ranged from 0.23 to 12 ppm (crude oils) to 0.43 ppm (No. 2 fuel oil) to 1.0 ppm (No. 6 fuel oil). For larvae, 2-d LC_{50} values ranged from 0.25 to 25 ppm (crude oils) to 1.3 ppm (No. 2 fuel oil) to 3.2 ppm (No. 6 fuel oil). For larval growth, 10-d EC_{50} values ranged from 0.05 to 2.1 ppm (crude oils) to 1.3 ppm (No. 2 fuel oil) to 1.6 ppm (No. 6 fuel oil).

The only study reporting effects of both chemically dispersed and whole oil on mollusc larvae is that of Renzoni (1973) using larvae of the oysters *Crassostrea angulata* and *C. gigas*, and of the mussel *Mytilus edulis*. In this study, nominal concentrations of both oil and oil/dispersant mixtures are reported. Very high nominal concentrations were toxic to the larvae. The toxicities of oil alone and oil/dispersant mixtures are reported as being similar.

Polychaetes

Lee and Nicol (1980) investigated toxicity of the WSF of No. 2 fuel oil to coastal polychaete larvae (mixed species). None were killed following a 2-d exposure to 50% WSF. Effects of dispersants and oil/dispersant mixtures have been investigated using nominal oil/dispersant concentrations and *Ophryotrocha labronica* larvae (Akesson 1975). Using Corexit 7664, LC_{50} values of 12,000 ppm were obtained. Using oil/dispersant mixtures (1:2, oil not further defined), LC_{50} values of 420 ppm were obtained.

Copepods

Because of their great importance in marine food webs, more data are available on the effects of oil and dispersants on copepods than on other kinds of zooplankton. However, much of this work is based on nominal concentrations and will not be considered further.

Sekerek and Foy (1978) reported a 4-d LC_{50} of 73 ppm for *Calanus hyperboreus* exposed to Prudhoe Bay crude water-accommodated fraction (WAF). Lee et al. (1980) reported that 4-d LC_{50} values for mixed species of copepods exposed to the WAF of *Ixtoc I* crude were >13.5 ppm.

Inhibition of feeding and depressed feeding rates in copepods exposed to oil have been reported by a number of authors. Berdugo et al. (1977) reported inhibition of feeding in the estuarine copepod *Eurytemora affinis* when exposed to 1.04 ppm of the WSF of heating oil for 24 h; feeding was depressed by exposure to 0.52 ppm for 24 h. Berman and Heinle (1980) reported "normal" feeding in the oceanic copepod *Acartia clausii* when exposed to 0.07 ppm No. 2 fuel oil; they reported inhibition of feeding in animals exposed to 0.25 ppm.

Berdugo et al. (1977) reported that 10-min to 4-h exposures to 3 ppm "fuel oil" in *Eurytemora affinis* resulted in reduced life span and fecundity. Ten-day exposures to the WSF of naphthalene (0.01 to 0.05 ppm) resulted in no reproductive effects. However, when Ott et al. (1978) exposed *E. affinis* females to 0.01 ppm naphthalene, fecundity was reduced 50%. The difference between the two experiments may result from exposure during different times of egg production.

Amphipods

Relatively few toxicity studies have been carried out with amphipod larvae. Linden (1976a) reported No. 2 fuel oil was more toxic to larval *Gammarus oceanicus* (2-d LC_{50} = 0.3 ppm) than crude oil (2-d LC_{50} = 0.8 ppm) or No. 4 fuel oil (2-d LC_{50} = 6.2 ppm). Lee and Nicol (1980) reported that exposure of embryos to 4 to 6 ppm of the WSF of No. 2 fuel oil caused juvenile *Parhyale hawaiensis* to weaken and die soon after hatching.

Linden (1976a) reported that larval growth rates in *Gammarus oceanicus* are significantly lowered during a 60-d exposure to 0.3 to 0.4 ppm weathered crude oil dispersion. When female *G. oceanicus* were exposed to the same oil dispersion for 23-d, fecundity was reduced (Linden 1976b).

Shrimp

No information was found concerning oil effects on adults or larvae of the pink shrimp *Penaeus duorarum*, a commercially important fishery species in South Florida.

Numerous studies have been carried out using larvae of several genera of shrimp. Anderson et al. (1974) investigated the toxicity of a number of crude and refined oils to post-larvae of the brown shrimp *Penaeus aztecus*; the WSF of South Louisiana crude was less toxic (4-d LC_{50} >19.8 ppm) than the WSF of either No. 2 fuel oil (4-d LC_{50} = 4.9 ppm) or No. 6 fuel oil (4-d LC_{50} = 1.9 ppm).

In a related series of experiments (Rice et al. 1976; Broderson et al. 1977; Mecklenberg et al. 1977), lethal and sublethal effects of the WSF of Cook Inlet crude on six larval stages of *Pandalus hypsinotus* were investigated. Four-day LC_{50} values for the larval stages are as follows: Stage 1 = 7.94 ppm; Stage 2 = 4.06 ppm; Stage 3 = 1,2 ppm; Stage 4 = 3.2 ppm; Stage 5 = 1.2 ppm; and Stage 6 = 0.54 ppm. Larvae molting from Stage 1 to Stage 2 were much more sensitive (4-d LC_{50} = 0.95 ppm) than either the Stage 1 larvae or the Stage 2 larvae. There was little difference between the toxicity of the WSF of Cook Inlet crude (4-d LC_{50} = 7.94 ppm) and the toxicity of the WSF of Prudhoe Bay crude (4-d LC_{50} = 8.53 ppm). Considerably less exposure to oil was required to produce morbidity, although the same relative order of sensitivity is retained except for Stage 2 larvae. The EC_{50} values for the larval stages are as follows:

Stage 1 = 1.8 ppm; Stage 2 = 0.8 ppm; Stage 3 = 0.35 ppm; Stage 4 = 1.9 ppm; Stage 5 = 0.96 ppm; and Stage 6 = 0.24 ppm.

The toxicity of the WSF of No. 2 fuel oil to both larvae and post-larvae of the grass shrimp *Palaemonetes pugio* has been investigated (Tatum et al. 1978). Larvae were more sensitive (4-d LC_{50} = 1.2 ppm) than post-larvae (4-d LC_{50} = 2.5 ppm).

Lobsters

No information was found concerning oil effects on larvae or adults of the spiny lobster *Panulirus argus*, a commercially and recreationally important fishery species in South Florida.

In a series of studies (Wells 1972; Wells and Sprague 1976), effects of crude oils on the larval development of the American lobster *Homarus americanus* were examined. The first larval stage and those larvae molting into second stage were most sensitive (4-d LC_{50} = 1 to 5 ppm). The 30-d LC_{50} was 0.14 ppm; at this level, the growth of surviving larvae was slowed.

Capuzzo et al. (1984) found that 96-h exposure to 0.25 ppm of the WSF of South Louisiana crude had no effect on survival of *Homarus americanus* larvae (Stages I to V). Reduced respiration and decreased O:N ratios were observed in all oil-exposed larvae. All oil-exposed larvae had slower growth rates, and all showed alterations in lipid metabolism (lower levels of triglycerides and increased levels of sterols). Early developmental stages of *H. americanus* are more sensitive to oil exposure than post-larvae. Capuzzo and Lancaster (1981) found no adverse effects of the WSF of South Louisiana crude on post-larval *H. americanus* after 78 d of exposure.

Crabs

No information was found concerning oil effects on larvae or adults of the stone crab *Menippe mercenaria*, a commercially and recreationally important fishery species in South Florida.

In a series of studies (Rice et al. 1976; Mecklenberg et al. 1977), toxicity of the WSF of Cook Inlet crude and Prudhoe Bay crude to the larvae of the Alaska king crab *Paralithodes camtschatica*, the Tanner crab *Chionoecetes bairdi*, and the Dungeness crab *Cancer magister* were examined. Using the WSF of Cook Inlet crude, 4-d LC_{50} values for Stage 1 *P. camtschatica* were 2 to 3 ppm; the 4-d LC_{50} value for larvae molting from Stage 1 to Stage 2 was 1.33 ppm. Using the WSF of Prudhoe Bay crude, the 4-d LC_{50} value was >6.4 ppm. Using the WSF of Cook Inlet crude, the 4-d LC_{50} for Stage 1 *C. bairdi* was >10.8 ppm. For Stage 1 *C. magister*, the 4-d LC_{50} for the WSF of Cook Inlet crude was >7.1 ppm; the 4-d LC_{50} for the WSF of Prudhoe Bay crude was >5.5 ppm.

As with the shrimp larvae, sublethal effects are observed at exposure levels considerably below the LC_{50} values. Rice et al. (1976) showed that the EC_{50} for immobilization of Stage 1 *Chionoecetes bairdi* larvae was 1.2 ppm for the WSF of Prudhoe Bay crude.

A number of studies have shown reduced rates of development and growth in crab larvae as a result of exposure to oil. Laughlin et al. (1978) showed that exposure to <1 ppm of the WSF of No. 2 fuel oil slowed the development of the mud crab *Rhithropanopeus depressus*. A 30-d exposure to 0.05 to 0.19 ppm of the WAF of No. 2 fuel oil delayed growth and development in the rock crab *Cancer irroratus*. These effects seem to be related to the presence of LMW aromatic hydrocarbons. The duration to the megalops stage in *R. depressus* was increased by exposure to phenanthrene and

decreased by exposure to naphthalene (Laughlin et al. 1978); exposure to phenanthrene (<0.15 ppm) always resulted in smaller larvae (Laughlin and Neff 1980).

Ichthyoplankton

No information was found concerning oil effects on eggs or larvae of any of the commercially important fish species in South Florida (see **Chapter 6** for discussion of common species in the ichthyoplankton).

The development of fish eggs and larvae is an extremely complex process which can be affected by oil exposure in many ways and at many different times during development. Increased mortality of fish eggs has been observed, with exposures ranging from 0.01 ppm (Longwell 1977) to 2.2 ppm (Linden et al. 1979). Reported 4-d EC_{50} values for fish eggs have ranged from 0.4 ppm (Sharp et al. 1979) to 43 ppm (Vuorinen and Axell 1980). In general, lesser exposures are required to cause delayed development of larvae (0.68 ppm, Smith and Cameron 1979), tissue pathologies in larvae (0.1 to 2.2 ppm, Vuorinen and Axell 1980), and morphological anomalies (0.68 ppm, Smith and Cameron 1979; 3.1 to 11.9 ppm, Linden 1978; 8.0 ppm, Davenport et al. 1980).

- Conclusions. Exposure to sub-ppm levels of oil affects many types of zooplankton. However, these effects are observed at exposure levels and times considerably in excess of levels likely to be observed under or near a slick of non-dispersed oil. Levels of chemically dispersed oil likely to be encountered as a result of dispersion of a slick with a normal amount of mixing may produce exposures high enough to affect zooplankton. However, these concentrations will be rapidly reduced by mixing. In situations where water circulation is more sluggish, such as in some shallow-water and nearshore areas, higher concentrations of both oil and dispersed oil may be encountered.

BENTHIC INVERTEBRATES

Corals

Early literature on the effects of oil and chemically dispersed oil on corals is contradictory. Oils and dispersants used are frequently not identified; exposure levels are frequently not measured. This literature has been critically reviewed (Knap et al. 1983) and will not be further discussed.

Effects of short-term (6 to 24 h) exposure to low levels (1 to 50 ppm) of Arabian Light crude, Arabian Light crude dispersed with BP1100WD (10:1) (ALC/BP), Arabian Light crude dispersed with Corexit 9527 (20:1) (ALC/CO), and dispersants alone on the brain coral *Diploria strigosa* have been thoroughly investigated (Knap 1987). Eight hours exposure to 19 ppm ALC/CO reduced photosynthesis of zooxanthellae by 85% and inhibited lipid synthesis. Oil alone and dispersants alone had no effect. Photosynthesis recovered within 3 to 5 h; lipid synthesis recovered within 24 h (Cook and Knap 1983).

Diploria strigosa exposed to 6 to 46 ppm Arabian Light crude, ALC/BP, and ALC/CO for 24 h in the laboratory and transplanted back into the field showed no abnormalities in growth (Dodge et al. 1984) or in calcification (Dodge et al. 1985) over a year's follow-up.

Diploria strigosa exposed to 14 to 16 ppm ALC/BP and 11 to 20 ppm ALC/CO for 24 h exhibited a variety of behavioral responses such as tentacle retraction and tissue swelling (Knap et al. 1985; Wyers et al. 1986). Tentacle retraction disappeared within 4 d. Tissue swelling sometimes persisted for 12 to 20 d; however, tissue swelling was also sometimes observed in control animals.

Knap and co-workers concluded that short-term exposure to levels of chemically dispersed oil expected following open-ocean dispersion of a slick would cause no permanent harm to *Diploria strigosa*.

Similar results have been reported by LeGore et al. (1989) who exposed natural assemblages of Arabian Gulf corals (largely *Acropora* spp.) to Arabian Light crude, ALC/CO, and dispersant alone. Exposure containers consisted of 2 m x 2 m x 3.5 m (depth) boomed plots. Booms were removed either 24 or 120 h following exposure. Two exposure scenarios were used. In the first, a one-time dispersal of a 0.25 mm slick was simulated. Dispersed-oil concentrations of 500 to 2,500 ppb were observed (most values were close to 500 ppb). Oil concentrations of 0 to 250 ppb were observed beneath the undispersed oil slick. Growth and colonization were followed for a year following exposure and were unaffected by any of the 24-h exposures.

The second scenario simulated dispersal of 0.1-mm slicks on each of five successive days. Concentrations of dispersed oil peaked each day following dispersion at about 2,500 ppb, and subsequently declined to about 500 ppb. Concentrations of oil observed under the non-dispersed slicks were 0 to 250 ppb. No effects of oil alone or dispersant alone were observed. In the dispersed oil plots, about 5% of the corals lost zooxanthellae and subsequently died during a cold spell. Growth of survivors and recruitment were unaffected over the ensuing year.

In a field experiment designed to yield a very high exposure of coral to dispersed oil, Ballou et al. (1989) exposed natural populations of *Porites porites* and *Agaricia tenuifolia* (living at depths from 10 cm to 3 m) to a 24-h continuous discharge of Prudhoe Bay crude dispersed by Corexit 9527 (20:1) and to Prudhoe Bay crude alone. Concentrations of C_1 to C_{10} LMW hydrocarbons averaged 293 ppb near the corals exposed to dispersed oil, whereas total hydrocarbon concentrations averaged 12.1 to 19.1 ppm at the same locations. Near the corals exposed to oil alone, LMW hydrocarbon concentrations averaged 33 ppb and total hydrocarbon concentrations averaged 1.4 to 2.5 ppm. Results of these exposures were that only 33% of *P. porites* exposed to dispersed oil survived; no *A. tenuifolia* survived. No recolonization was observed 20 months post-exposure. No adverse effects on corals were observed at the non-dispersed oil site.

This experiment simulates dispersing a large amount of oil into a very poorly flushed environment. The continuous addition of fresh, dispersed oil over a 24-h period provided the highest possible dose of acutely toxic compounds. This is a much more severe exposure than those simulating a one-time dispersion of a slick.

- Conclusions. It seems clear that effects of oil or dispersed oil on corals will be very dependent on the delivered dose in any given situation. This can be seen by contrasting effects of one-time dispersion (Knap 1987; LeGore et al. 1989; 24 h), successive dispersions (LeGore et al. 1989; 120 h), and 24-h continuous discharge (Ballou et al. 1989). Hence, conclusions drawn about the probable effects of oil or dispersed oil are highly dependent on the particular situation being evaluated.

Molluscs

Most of the information concerning oil effects on molluscs has been obtained from field experimentation. No information was found concerning effects of oil on queen conch *Strombus gigas*, a commercially and recreationally important fishery species in South Florida.

Survival

Shuba and Heikamp (1989), in experiments with the oyster *Crassostrea virginica*, determined that the LC_{50} for chemically dispersed (Corexit 9527; 10:1) Arabian Light crude was in excess of 2,500 ppm. There are numerous accounts of various bivalves living in sediments containing more than 1,000 ppm of various hydrocarbons.

Sublethal Effects

Byrne and Calder (1977) found that the EC_{50} for growth in straight-hinge bivalve larvae of *Mercenaria* sp. was 290 ppb for Jay crude and 15.7 ppm for Kuwait crude.

Roesijadi and Anderson (1979) found that 55-d exposure to 1,000 ppm Prudhoe Bay crude in sediments significantly reduced the condition index in the bivalve *Macoma iniquinata*. Augenfeld et al. (1980) found that exposure of the bivalve *Prototheca staminea* to sediments containing 1,237 ppm Prudhoe Bay crude resulted in a 6% reduction in the condition index. The reduction in condition index in *P. staminea* was much less than that in *M. iniquinata*. Augenfeld et al. (1980) hypothesized that *P. staminea*, a filter feeder, is less affected than *M. iniquinata*, a deposit feeder, because *P. staminea* is in less intimate contact with the sediment.

Anderson et al. (1985) studied effects of Prudhoe Bay crude and chemically dispersed (Corexit 9527, 10:1) Prudhoe Bay crude in sediments on growth and survival of *Macoma iniquinata* and *Prototheca staminea*. In a one-month comparison of survival in oil and dispersed oil (2,000 ppm in sediments), *P. staminea* survived better in dispersed oil (80%) than in oil (43%). The same pattern was seen in results for *M. iniquinata*; survival in dispersed oil (44% and 40%) was better than in oil (10% and 12%). Once again, the deposit feeder *M. iniquinata* fared less well than the filter feeder *P. staminea*. A four-month study showed there was no difference between effects of oil and dispersed oil on growth in *P. staminea*. In a six-month study, dispersed oil was found to reduce growth more than oil did. However, the initial concentration of dispersed oil was 3,508 ppm; the initial concentration of oil was 2,241 ppm. Hence, the observed differences in growth could have been caused by the increased concentration of dispersed oil. It should be pointed out that in this study, the dispersed oil was added to the sediment before it had a chance to disperse in seawater. This is an unrealistic scenario for simulating anything except the application of dispersant to oil lying on a beach, which is never recommended.

- Conclusions. Many species of molluscs are very resistant to oil effects. Lethality can be expected only when large amounts (>1,000 ppm) are incorporated into sediments. Sublethal effects can be expected at lower levels.

Annelids

The effects of oiled sediments on feeding and nutrition of lugworms has been investigated.

Prouse and Gordon (1976) found that concentrations up to 25.9 ppm of No. 6 fuel in sediments had no effect on feeding of the polychaete *Arenicola marina*. Concentrations ranging from 87.1 to 249.2 ppm reduced feeding by 33 to 50%.

Augenfeld (1980) showed that sediment concentrations of 500 to 1,000 ppm Prudhoe Bay crude reduced feeding in the polychaete *Abarenicola pacifica* by 70%. Smaller worms were more severely affected than larger ones. Augenfeld et al. (1983) showed that feeding in *A. pacifica* was reduced by exposure to 250 ppm Prudhoe Bay crude in sediment and that glycogen content of the worms was significantly reduced by exposure to 500 ppm Prudhoe Bay crude in sediments.

Rossi and Anderson (1978) showed that growth in the polychaete *Neanthes arenaceodentata* decreased as the concentration of the WSF of No. 2 fuel oil increased (60 to 181 ppb total naphthalenes). After three generations of oil exposure, the worms were more resistant to oil effects. Similar effects were observed by Neff et al. (1976). Presumably this reflects selection for increased mixed function oxidase (MFO) activity as observed by Lee and Singer (1980) in the polychaete *Capitella capitata.*

- Conclusions. Significant effects on feeding in lugworms can be expected at sediment oil concentrations which can easily occur in oil spill situations. Reduced growth can also be expected if significant amounts of oil are incorporated into sediments.

Crustaceans

Because many species of crustaceans are easily handled in the laboratory, there is a significant amount of information available on oil effects in this group of animals. The discussion will be separated by type of response.

Survival

Anderson et al. (1984, 1987) determined toxicity of dispersed Prudhoe Bay crude to the shrimp *Pandalus danae.* They found that LC_{50} values in this species are higher in winter (10 to 12 ppm) than in summer (2.5 to 8 ppm). They further found that most of the toxicity of Prudhoe Bay crude resides in the monoaromatic fraction. When the monoaromatics were removed by distillation (simulating weathering), summer LC_{50} values increased to 22 ppm and winter values increased to 61 ppm. When both mono- and di-aromatics were removed by distillation (simulating further weathering), summer LC_{50} values exceeded 55 ppm, and winter values exceeded 240 ppm.

Shuba and Heikamp (1989) investigated the toxicity of chemically dispersed (Corexit 9527; 10:1) Arabian Light and Mayan crudes to the blue crab *Callinectes sapidus*, the brown shrimp *Penaeus aztecus*, and the white shrimp *P. setiferus*. Using Arabian Light crude, the following 96-h LC_{50} values were found: *C. sapidus*, 49 ppm; *P. aztecus*, >18.8 ppm; and *P. setiferus*, 44 ppm. Using Mayan crude, the 96-h LC_{50} value for *P. aztecus* was 23 ppm, and for *P. setiferus*, >16 ppm.

Sublethal Effects

Edwards (1978) exposed the shrimp *Crangon crangon* to 0, 5, 10, 20, and 35% WSF of North Sea (Brent) crude (100% WSF = 19 ppm) at three different temperatures (10 °C, 15 °C, and 20 °C). Scope for growth was reduced by increased concentrations of the WSF at all temperatures, as was the animals' growth rate. Neff et al. (1976) exposed the grass shrimp *Palaemonetes pugio* to the WSF of No. 2 fuel oil (270 to 340 ppb naphthalenes) for 28 d and observed significantly reduced growth.

- Conclusions. Commercially important crustacea in the study area are unlikely to be killed by dispersion of oil slicks in the open sea. If oil enters confined areas, lethality is a definite possibility. In case of significant oil contamination of sediments, sublethal effects are likely in the immediate area of the oiled sediments.

VERTEBRATES

Fish

Fish can be affected by oil ingested in their prey and by uptake of dissolved oil. Oil effects on fish are known from relatively few species, all of which are temperate. The sensitivity of fish to oil varies widely. In general, pelagic species seem more tolerant than demersal species; intertidal fish are most tolerant to oil (Rice et al. 1979).

Natural stresses arising from changes in temperature and salinity or low food availability can exacerbate responses to oil (Levitan and Taylor 1979; Englehardt et al. 1981). Parasitic infestation can also reduce the ability of fish to withstand oil stress (Moles 1980). A wide variety of physiological responses of fish to oiling has been reported (NRC 1985). This literature has little value for predicting oil effects on fish and will not be further reviewed. Oil effects on fish reproduction have been covered in the Ichthyoplankton section of this chapter.

Fish possess an MFO system in their liver and can metabolize hydrocarbons; both metabolites and hydrocarbons can be excreted in bile or through the gills. Use of the MFO system is not without cost. It is energetically expensive and may lead to liver damage. English sole *Parophrys vetulus* maintained on oiled sediment had very low levels of hydrocarbons in their tissues, but experienced high weight loss and liver abnormalities relative to control fish (McCain et al. 1978). There is concern that some metabolites of aromatic hydrocarbons may be carcinogenic. Recently, Varanasi et al. (1989a,b) found PAH adducts in the liver of *P. vetulus* exposed to benzo(a)pyrene in the laboratory and in the livers of wild fish exposed to PAHs in the field. These same fish had a high incidence of liver neoplasia.

Decreased growth has been observed in a number of species following oil exposure: coho salmon *Oncorhynchus kisutch* (Moles et al. 1981); cutthroat trout *Salmo clarki* (Woodward et al. 1981); English sole *Parophrys vetulus* (McCain et al. 1978); and pink salmon *O. gorbuscha* alevins (Rice et al. 1975; Moles and Rice 1983). Decreased growth has been observed at hydrocarbon exposure concentrations that are about 10% (0.1 to 1 ppm) of acute lethal values (1 to 10 ppm) (Rice 1985). The lower part of this range is comparable with concentrations of oil found under major oil slicks (100 to 200 ppb), but it is important to remember that these results are from long-term exposure experiments.

Exposure to oil has also been associated with increased fin erosion (Minchew and Yarbrough 1977) and decreased rates of tissue regeneration (Fingerman 1980).

No studies of dispersed oil effects on adult fish, other than studies of effects on salmon homing ability, seem to have been performed.

- Conclusions. Acute exposure of fish to concentrations of oil expected under undispersed oil slicks is unlikely to be lethal to adult fish. Chronic exposure of fish to low levels of oil (100 to 1,000 ppb) can cause reduced growth, impairment of liver function, and increased incidence of liver neoplasia. Exposure of adult fish to concentrations of 5 to 10 ppm of many oils will lead to death.

Sea Turtles

Very little information is available concerning the effects of petroleum on sea turtles. In a series of related experiments, Vargo et al. (1986) exposed young (3 to 20 month) green sea turtles (*Chelonia mydas*) and loggerhead sea turtles (*Caretta caretta*) to slicks of South Louisiana crude. They found that turtles can detect and avoid slicks. In

the presence of oil slicks, turtles tend to spend more time underwater. Feeding experiments yielded no evidence that turtles would selectively strike at tar balls.

Exposure of turtles to 0.5-mm slicks for 96 h in tanks led to no alteration in metabolic rate (Vargo et al. 1986). There were indications of possible liver dysfunction; the immune system was activated by exposure to oil. The most serious response was sloughing off of the outer layers of skin. The skin recovered within one month.

Exposure of turtles to a 5-mm slick for 24 h produced similar symptoms to those seen in turtles exposed to the 0.5-mm slick (Vargo et al. 1986). However, the responses were more acute. Respiration increased; some turtles were in distress. The immune response was greater. Salt gland function was inhibited, but recovered within two weeks. Skin sloughing was more severe, but healed within a month.

Turtles lay their eggs in nests in the sand near the high-tide line. Given the effects of oil on the hatchability of bird eggs, oiling of turtle nesting beaches is a major concern. The effects of oiling on hatchability of turtle eggs has been studied by Fritts and McGehee (1982). Using split clutches, they compared hatching success of Kemp's ridley sea turtle (*Lepidochelys kempi*) eggs incubated in clean dune sand and in sand from the nesting beach which contained weathered *Ixtoc I* crude. There was no significant difference in hatching success between the two sands.

In laboratory experiments using eggs of the loggerhead sea turtle *Caretta caretta*, it was found that adding 0, 7.5, 15, or 30 mL South Louisiana crude to 4 kg of sand prior to incubation had no effect on hatching success of the eggs. However, adding 30 mL South Louisiana crude after either 28 or 42 d of incubation dramatically reduced hatching success (Fritts and McGehee 1982).

- Conclusions. Exposure of sea turtles to floating oil may cause adverse physiological alterations in the turtles and make them more vulnerable to bacterial infection. Turtle nesting beaches should be protected from oiling while the eggs are incubating.

Birds

Birds are the most conspicuous casualties resulting from oil pollution incidents. Oil contamination of bird feathers damages their water-repellent properties (Kennedy 1970). When air trapped in the feathers is replaced by water, the bird loses buoyancy and may sink and drown (Holmes and Cronshaw 1977). At the same time, the insulating properties of the feathers are destroyed, and the metabolic rate must be greatly increased to maintain body temperature (Hartung 1967). When fat and other energy reserves are exhausted, the birds die (Croxall 1977). Tropical birds may be less at risk from hypothermia than temperate birds (Brown 1982). It is not clear what degree of oiling is required to kill birds. Some birds (e.g., Common Murres, *Uria aalge*; Great Black-backed Gulls, *Larus marinus*; and Razorbills, *Alca torda*--none of which are found in South Florida) seem to be able to clean themselves by preening (Birkhead et al. 1973). Oil ingested by preening birds may cause physiological alterations similar to those observed in birds fed oil experimentally (see paragraph below). Robertson and Robertson (1982) reported that periodic oiling by pelagic tar does not affect survival or reproductive ability in Sooty Terns (*Sterna fuscata*) living on the Dry Tortugas.

Numerous pathological abnormalities have been observed in stranded oiled birds (Croxall 1977; Brown 1982). It is not clear whether these abnormalities are the proximate cause of death of these animals. Abnormally high levels of MFO activity were observed in livers of birds oiled by the *Amoco Cadiz* oil spill (Vandermeulen et al. 1978).

Changes in osmoregulation (Holmes 1975; Peakall et al. 1982), induction of MFO activity (Gorsline et al. 1981), reduced weight gain (Miller et al. 1978), and weight loss (Peakall et al. 1985) have all been observed in birds fed oil in experiments.

Ingestion of oil can also cause temporary interference with egg laying and may interfere with hatchability of eggs produced by Cassin's Auklet (*Ptychoramphus aleuticus*) (Ainley et al. 1981). In this species, ingestion of 0.6 g No. 6 fuel oil had no effect on egg laying, but ingestion of 1 g did have an effect.

Small quantities of oil applied to eggs can kill the embryo within. As little as 1 μL of oil can kill embryos in eggs of Mallards (*Anas platyrhynchos*); 20 μL are required to kill embryos in eggs of Common Eiders (*Somateria mollissima*) (Szaro 1977; Szaro and Albers 1977). It is not at all clear that oiling of eggs is a serious problem in nature.

Experiments show that Prudhoe Bay crude and chemically dispersed (Corexit 9527) Prudhoe Bay crude have about the same toxicity to *Anas platyrhynchos* eggs when applied to the surface (Albers and Gay 1982). Peakall et al. (1982) have shown that Prudhoe Bay crude and crude/Corexit 9527 mixtures caused similar weight loss when painted on Herring Gulls (*Larus argentatus*). Butler et al. (1988) showed that Prudhoe Bay crude/Corexit 9527 mixtures painted on adult Leach's Storm-Petrels (*Oceanodroma leucorhoa*) caused greater mortality and less weight gain than Prudhoe Bay crude alone.

Chemically dispersed oil goes readily into solution. It is not clear what exposure scenario these experiments are designed to simulate. They clearly show that prior to dispersion, oil/dispersant mixtures are about as toxic as the oil that they are made with. It is not clear what insight the results of these experiments give on the interaction between chemically dispersed oil and seabirds in the field.

- Conclusions. Birds are likely to be affected by floating oil slicks. Chemical dispersion which removes the slick from the surface will reduce the risk to birds.

Dolphins

Little is known about interactions between dolphins and petroleum. Bottlenose dolphins (*Tursiops truncatus*) are capable of detecting floating oil slicks (Geraci et al. 1983). Slicks seem to be detected visually; the mechanism breaks down at night (Geraci and St. Aubin 1985). Once dolphins have detected a slick, they avoid it (Smith et al. 1983).

Healthy cetacean skin is important in preventing infection. Exposure for up to 60 min to a gasoline-soaked sponge had no effect on the health of dolphin skin (Geraci and St. Aubin 1985).

No information is available on the effects of dispersed oil on dolphins.

- Conclusions. Dolphins are intelligent and highly mobile, and they are able to detect and avoid slicks, except at night. The major organ at risk is the skin, which seems to be resistant to oil damage.

Manatees

No information exists concerning the toxicity of oil or chemically dispersed oil to manatees.

CONCLUSIONS

Review of the toxicological literature shows no consistent differences in toxicity between tropical, subtropical, temperate, and arctic species. As a result, with some notable exceptions (discussed below), the same data base that the Minerals Management Service uses to make regulatory decisions in other outer continental shelf areas will be appropriate to South Florida.

Major injuries to plant and animal species will be expected when significant amounts of oil are incorporated into intertidal sediments. Effects on water column organisms are not expected from exposure to undispersed oil or dispersed oil in normally dispersive environments. In more retentive environments (shallow-water areas with sluggish circulation) which yield longer exposures to higher levels of oil, water column effects will become more likely. This is particularly true of exposures to dispersed oil. Dispersant use decisions in shallow, slow-circulating water will have to be viewed as a trade-off, i.e., preventing incorporation of oil into sediments in some parts of the environment at the expense of temporarily exposing water column and epibenthic species to levels of dispersed oil that may be harmful to them.

Based on the available toxicological literature, mangroves and birds seem to be most vulnerable to oil spills; polychaetes, molluscs, seagrasses, and attached algae seem to be most resistant to oil spill effects. The increased complexity of subtropical and tropical ecosystems may make them somewhat more resilient with respect to oil spill effects than temperate and arctic ecosystems.

Significant data gaps and information needs identified during this review are summarized below, in order of priority:

- **Manatees**. No information exists on the effects of oil on manatees. Experimentation with these animals would be extremely difficult because of their Endangered status. Efforts can be made to collect information on manatee effects associated with "spills of opportunity." This can be done on a small scale in Florida. A greater opportunity may lie in the accidental exposure of many dugongs to oil during the Persian Gulf War. Some scientific observations may have been made by regional scientists at the time. It will be worth an effort to find out whether this information exists.

- **Corals**. Corals are extremely important in that they create habitat for many other species (see **Chapter 4**). The great majority of information available to date has been obtained using one species, the brain coral *Diploria strigosa*. Efforts should be made to determine the toxicity of oil and chemically dispersed oil to other species of corals common in South Florida.

- **Coralline algae**. Coralline algae are very important in the development of coral reefs. No information is available concerning the toxicity of oil or chemically dispersed oil to these algae.

- **Commercially and recreationally important shellfish and finfish**. Despite an extensive literature search, no information was found concerning effects of oil or chemically dispersed oil on larvae or adults of the following commercially and recreationally important shellfish species: pink shrimp *Penaeus duorarum*; spiny lobster *Panulirus argus*; stone crab *Menippe mercenaria*; and queen conch *Strombus gigas*. Data on the sensitivity of these species to oil and chemically dispersed oil should be obtained so as to compare their sensitivity with that of related species. Data should be obtained for either larvae or post-larvae, as these are likely to be the most sensitive stages of the life cycle. Data are also lacking for eggs and larvae (ichthyoplankton) of commercially important finfish in South Florida.

- **Seagrasses**. Seagrasses are also important in creating habitat for many other species (**Chapter 4**). Most of the experimental work on these species has been done in static culture. Although results indicate that seagrasses are very resistant to oil and chemically dispersed oil, this work should be redone in flow-through culture.

- **Sea turtles and dolphins**. There is some information available on oil effects on turtles and dolphins. The basic outline of oil toxicity in these species seems to be known. Further confirmatory information would be useful.

REFERENCES CITED

Ainley, D. G., C. R. Grau, T. E. Roudybush, S. H. Morrell, and J. M. Utts. 1981. Petroleum ingestion reduces reproduction in Cassin's Auklets. *Mar. Pollut. Bull.* 12:314-317.

Akesson, B. 1975. Bioassay studies with polychaetes of the genus *Ophryotrocha* as test animals. In *Sublethal effects of toxic chemicals on aquatic animals*, ed. J. H. Koeman and J.J.T.W.A. Strick, 121-135. New York: Elsevier.

Albers, P. H., and M. L. Gay. 1982. Effects of a chemical dispersant and crude oil on breeding ducks. *Bull. Environ. Contam. Toxicol.* 29:404-411.

Anderson, J. W., J. M. Neff, B. A. Cox, H. E. Tatum, and G. H. Hightower. 1974. Characteristics of dispersions and water soluble extracts of crude and refined oil and their toxicity to estuarine crustaceans and fish. *Mar. Biol.* 27:75-88.

Anderson, J. W., S. L. Kiesser, D. L. McQuerry, and M. L. Fleischman. 1984. Toxicity testing with constant or decreasing concentrations of chemically dispersed oil. In *Oil spill chemical dispersants: Research, experience and recommendations*, ed. T. E. Allen, 14-22. Philadelphia: American Society for Testing and Materials. STP840.

Anderson, J. W., S. L. Keisser, D. L. McQuerry, and G. W. Fellingham. 1985. Effects of oil and chemically dispersed oil in sediments on clams. In *Proceedings, 1985 Oil Spill Conference*, 349-353. Washington, DC: American Petroleum Institute.

Anderson, J. W., R. Riley, S. Kieser, and J. Gurtisen. 1987. Toxicity of dispersed and undispersed Prudhoe Bay crude oil to fish and shrimp. In *Proceedings, 1987 Oil Spill Conference*, 235-240. Washington, DC: American Petroleum Institute.

Augenfeld, J. M. 1980. Effects of Prudhoe Bay crude oil contamination on sediment working rates of *Abarenicola pacifica*. *Mar. Environ. Res.* 3:307-313.

Augenfeld, J. M., J. W. Anderson, D. L. Woodruff, and J. L. Webster. 1980. Effects of Prudhoe Bay crude oil contaminated sediments on *Prototheca staminea* (Mollusca: Pelecypoda): Hydrocarbon content, condition index, free amino acid level. *Mar. Environ. Res.* 4:135-143.

Augenfeld, J. M., J. W. Anderson, S. L. Kiesser, G. W. Fellingham, R. G. Riley, and B. L. Thomas. 1983. Exposure of *Abarenicola pacifica* to oiled sediment: Effects on glycogen content and alterations in sediment bound hydrocarbons. In *Proceedings, 1983 Oil Spill Conference*, 443-449. Washington, DC: American Petroleum Institute.

Baca, B. J., and C. D. Getter. 1982. The toxicity of oil and chemically dispersed oil to the seagrass *Thalassia testudinum*. In *Oil spill chemical dispersants: Research, experience and recommendations*, ed. T. E. Allen, 314-323. Philadelphia: American Society for Testing and Materials. STP840.

Ballou, T. G., R. E. Dodge, S. C. Hess, A. H. Knap, and T. D. Sleeter. 1987. *Effects of dispersed and undispersed crude oil on mangroves, seagrasses and corals*. Washington, DC: American Petroleum Institute. API Publ. No. 4460.

Ballou, T. G., S. C. Hess, R. E. Dodge, A. H. Knap, and T. D. Sleeter. 1989. Effects of untreated and chemically dispersed oil on tropical marine communities: A long term field experiment. In *Proceedings, 1989 Oil Spill Conference*, 447-454. Washington, DC: American Petroleum Institute.

Batterton, J. C., K. Winters, and C. Van Baalen. 1978. Sensitivity of three microalgae to crude oils and fuel oils. *Mar. Environ. Res.* 1:31-41.

Berdugo, V., R. P. Morris, and S. C. O'Hara. 1977. The effect of petroleum hydrocarbons on reproduction of an estuarine planktonic copepod in laboratory cultures. *Mar. Pollut. Bull.* 8:138-143.

Berman, M. S., and D. R. Heinle. 1980. Modification of the feeding behavior of marine copepods by sub-lethal concentrations of water-accommodated fuel oil. *Mar. Biol.* 56:59-64.

Birkhead, T. R., C. Lloyd, and P. Corkhill. 1973. Oiled seabirds successfully cleaning their plumage. *Br. Birds*. 66:535-537.

Bokn, T. 1985. Effects of diesel oil on commercial benthic algae in Norway. In *Proceedings, 1985 Oil Spill Conference*, 491-496. Washington, DC: American Petroleum Institute.

Broderson, C. C., S. D. Rice, J. W. Short, T. A. Mecklenberg, and J. F. Karinen. 1977. Sensitivity of larval and adult Alaskan shrimp and crabs to acute exposures of the water soluble fraction of Cook Inlet crude oil. In *Proceedings, 1977 Oil Spill Conference*, 575-578. Washington, DC: American Petroleum Institute.

Brown, R. G. B. 1982. Birds, oil and the Canadian environment. In *Oil and dispersants in Canadian seas - Research appraisal and recommendations*, ed. J. B. Sprague, J. H. Vandermeulen, and P. G. Wells. Environment Canada, Environmental Protection Service. Economic and Technical Rep. EPS-3-EC-82-2.

Butler, R. G., A. Harfenist, F. A. Leighton, and D. B. Peakall. 1988. Impact of sublethal oil and emulsion exposure on the reproductive success of Leach's Storm Petrels: Short and long term effects. *J. Appl. Ecol.* 25:125-143.

Byrne, C. J., and J. A. Calder. 1977. Effect of the water soluble fractions of crude, refined and waste oils on the embryonic and larval stages of the quahog clam *Mercenaria*. *Mar. Biol.* 40:225-231.

Capuzzo, J. M., and B. A. Lancaster. 1981. Physiological effects of South Louisiana crude oil on larvae of the American lobster (*Homarus americanus*). In *Biological monitoring of marine pollutants*, ed. F. J. Vernberg, A. Calabrese, F. P. Thurberg, and W. B. Vernberg, 405-423. New York: Academic Press.

Capuzzo, J. M., B. A. Lancaster, and G. C. Sasaki. 1984. Effects of petroleum hydrocarbons on lipid metabolism and energetics of larval development and metamorphosis in the American lobster (*Homarus americanus* Milne Edwards). *Mar. Environ. Res.* 14:201-228.

Cook, C. B., and A. H. Knap. 1983. Effects of crude oil and chemical dispersant on photosynthesis in the brain coral, *Diploria strigosa*. *Mar. Biol.* 78:21-27.
Croxall, J. P. 1977. The effects of oil on seabirds. *Rapp. P.-V. Réun. CIEM* 171:191-195.
Davenport, J., S. Lonning, and L. J. Saethre. 1980. The effects of Ekofisk oil extract on oxygen uptake in eggs and larvae of the cod *Gadus mohura*. *Astarte* 12:31-34.
Dicks, B. 1986. Oil and the black mangrove, *Avicennia marina* in the northern Red Sea. *Mar. Pollut. Bull.* 17:500-503.
Dodge, R. E., S. C. Wyers, H. R. Frith, A. H. Knap, S. R. Smith, and T. D. Sleeter. 1984. The effects of oil and oil dispersants on the skeletal growth of the hermatypic coral, *Diploria strigosa*. *Coral Reefs* 3:191-198.
Dodge, R. E., A. H. Knap, S. C. Wyers, H. R. Frith, T. D. Sleeter, and S. R. Smith. 1985. The effect of dispersed oil on the calcification rate of the reef building coral *Diploria strigosa*. In *Proceedings, 5th International Coral Reef Congress* 6:453-457.
Edwards, R. R. C. 1978. Effects of water soluble oil fractions on metabolism, growth and carbon budget of the shrimp, *Crangon crangon*. *Mar. Biol.* 46:259-265.
Englehardt, F. R. 1985. Effects of petroleum on marine mammals. In *Petroleum effects in the arctic environment*, ed. F. R. Englehardt, 217-244. London: Elsevier Applied Science Publishers.
Englehardt, F. R, M. P. Wong, and M. E. Duey. 1981. Hydro-mineral balance and gill morphology in rainbow trout acclimated to fresh and seawater, as affected by petroleum exposure. *Aquat. Toxicol.* 1:175-186.
Fingerman, S. W. 1980. Differences in the effects of fuel oil, an oil dispersant and three polychlorinated biphenyls on fin regeneration in the Gulf coast killifish, *Fundulus grandis*. *Bull. Environ. Contam. Toxicol.* 25:234-240.
Fritts, T. H., and M. A. McGehee. 1982. *Effects of petroleum on the development and survival of marine turtle embryos*. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.
Geraci, J. R., and D. J. St. Aubin. 1985. Expanded studies on the effects of oil on cetaceans. Contract No. 14-12-0001-30293. Washington, DC: U.S. Department of the Interior, Minerals Management Service.
Geraci, J. R., D. J. St. Aubin, and R. J. Reisman. 1983. Bottlenose dolphins, *Tursiops truncata*, can detect oil. *Can. J. Fish. Aquat. Sci.* 40:1516-1522.
Geraci, J. R., and D. J. St. Aubin, ed. 1988. *Synthesis of effects of oil on marine mammals*. OCS Study MMS 88-0049. Washington, DC: U.S. Department of the Interior, Minerals Management Service.
Getter, C. D., and B. J. Baca. 1984. A laboratory approach for determining the effect of oils and dispersants on mangroves. In *Oil spill chemical dispersants: Research, experience and recommendations*, ed. T. E. Allen, 5-13. Philadelphia: American Society for Testing and Materials. STP840.
Getter, C. D., and T. G. Ballou. 1985. Field experiments on the effects of oil and dispersant on mangroves. In *Proceedings, 1985 Oil Spill Conference*, 527-582. Washington, DC: American Petroleum Institute.
Gorsline, J., W. N. Holmes, and J. Cronshaw. 1981. The effects of ingested petroleum on the naphthalene metabolizing properties of liver tissue in sea water adapted mallard ducks (*Anas platyrhynchos*). *Environ. Res.* 24:372-390.
Hannan, R. P., and L. A. Phillips. 1975. *The effects of selected petroleum refinery products and crude oils on seeds and seedlings of the black mangrove, Avicennia germinans L.* Progress Rep. 9A. Unpubl. report submitted to the U.S. Environmental Protection Agency by General Electric/National Space Technology Laboratories.
Hartung, R. 1967. Energy metabolism in oil-covered ducks. *J. Wildl. Manage.* 31:798-804.
Holmes, W. N. 1975. Hormones and osmoregulation in marine birds. *Gen. Comp. Endocrinol.* 25:249-258.
Holmes, W. N., and J. Cronshaw. 1977. Biological effects of petroleum on marine birds. In *Effects of petroleum on arctic and subarctic marine environments and organisms, Vol. 2*, 359-398. New York: Academic Press.
Hutchinson, T. C., J. A. Hellebust, D. Mackay, D. Tamm, and P. B. Kauss. 1979. The relation of hydrocarbon solubility to toxicity and cellular membrane effects. In *Proceedings, 1985 Oil Spill Conference*, 541-547. Washington, DC: American Petroleum Institute.
Jackson, J. B. C., J. D. Cubit, B. D. Keller, V. Batista, K. Burns, H. M. Caffey, R. L. Caldwell, S. D. Garrity, C. D. Getter, C. Gonzalez, H. M. Guzman, K. W. Kaufmann, A. H. Knap, S. C. Levings, M. J. Marshall, R. Steger, R. C. Thompson, and E. Weil. 1989. Ecological effects of a major oil spill on Panamanian coastal marine communities. *Science* 243:37-44.
Kaas, R. 1981. Evolution des peuplements algaux explitables depuis le nauffrage de L'*Amoco Cadiz*. In *Amoco Cadiz: Fates and effects of the oil spill*, 687-702. Paris: Centre National Pour L'Exploitation des Oceans.
Kennedy, R. J. 1970. Directional water-shedding properties of feathers. *Nature* 227:736-737.
Knap, A. H. 1987. Effects of chemically dispersed oil on the brain coral, *Diploria strigosa*. *Mar. Pollut. Bull.* 18:119-122.
Knap, A. H., T. D. Sleeter, R. E. Dodge, S. C. Wyers, H. R. Frith, and S. R. Smith. 1983. The effects of oil spills and dispersant use on corals: A review and multidisciplinary approach. *Oil Petrochem. Pollut.* 1:157-169.
Knap, A. H., S. C. Wyers, R. E. Dodge, T. D. Sleeter, H. R. Frith, S. R. Smith, and C. B. Cook. 1985. The effects of chemically and physically dispersed oil on the brain coral, *Diploria strigosa* (Dana) - A summary review. In *Proceedings, 1985 Oil Spill Conference*, 547-551. Washington, DC: American Petroleum Institute.
Lai, H-C. and M-C. Feng. 1985. Field and laboratory studies on the toxicity of oils to mangroves. In *Proceedings, 1985 Oil Spill Conference*, 539-546. Washington, DC: American Petroleum Institute.
Lanier, J. J., and M. Light. 1978. Ciliates as bioindicators of oil pollution. In *Proceedings, Conference on Assessment of Ecological Impacts of Oil Spills*, 651-676. Washington, DC: American Institute of Biological Sciences. NTIS No. AD-A072 859.
Laughlin, R. B., Jr., and J. M. Neff. 1980. Influence of temperature, salinity and phenanthrene (a petroleum derived polycyclic aromatic hydrocarbon) on the respiration of larval mud crabs, *Rhithropanopeus harrisii*. *Estuar. Coast. Mar. Sci. 10:655-669.*
Laughlin, R. B., Jr., L. G. L. Young, and J. M. Neff. 1978. A long term study of the effects of water soluble fractions of no. 2 fuel oil on the survival, development rate and growth of the mud crab *Rhithropanopeus harrisii*. *Mar. Biol.* 47:87-95.
Lee, R. F. 1975. Fate of petroleum hydrocarbons in marine zooplankton. In *Proceedings, 1975 Oil Spill Conference*, 549-553. Washington, DC: American Petroleum Institute.
Lee, R. F., and J. W. Anderson. 1977. Fate and effect of naphthalenes in controlled ecosystem enclosures. *Bull. Mar. Sci. 27*:127-134.
Lee, R. F., and S. C. Singer. 1980. Detoxifying enzyme system in marine polychaetes: Increases in activity after exposure to aromatic hydrocarbons. *Rapp. P.-V. Réun. CIEM* 179:29-32.
Lee, R. F., and M. Takahashi. 1977. The fate and effect of petroleum in controlled ecosystem enclosures. *Rapp. P.-V. Réun. CIEM* 171:150-156.
Lee, W. Y., and J. A. C. Nicol. 1980. Toxicity of a fuel oil to the eggs of *Parhyale hawaiensis* and *Amphithoe valida* (Amphipoda). *Mar. Environ. Res.* 3:297-305.

Lee, W. Y., A. Morris, and D. Boatwright. 1980. Mexican oil spill: A toxicity study of oil accommodated in seawater on marine invertebrates. *Mar. Pollut. Bull.* 11:231-234.
LeGore, S., D. S. Marszalek, L. Danek, M. S. Tomlinson, J. E. Hoffman, and J. E. Cuddeback. 1989. Effect of chemically dispersed oil on Arabian Gulf corals: A field experiment. In *Proceedings, 1989 Oil Spill Conference*, 375-380. Washington, DC: American Petroleum Institute.
Leighton, F. A., R. G. Butler, and D. B. Peakall. 1985. Oil and arctic marine birds: An assessment of risk. *In Petroleum effects in the arctic environment*, ed. F. R. Englehardt, 183-216. London: Elsevier Applied Science Publishers.
Levitan, W. M., and M. H. Taylor. 1979. Physiology of salinity-dependent naphthalene toxicity in *Fundulus heteroclitus*. *J. Fish. Res. Bd. Can.* 36:615-620.
Linden, O. 1976a. Effects of oil on the amphipod *Gammarus oceanicus*. *Environ. Pollut.* 10:239-250.
Linden, O. 1976b. Effects of oil on the reproduction of the amphipod *Gammarus oceanicus*. *Ambio* 5:36-37.
Linden, O. 1978. Biological effects of oil on early development of the Baltic herring *Clupea harengus membras*. *Mar. Biol.* 45:273-283.
Linden, O., J. R. Sharp, R. Laughlin, Jr., and J. M. Neff. 1979. Interactive effects of salinity, temperature and chronic exposure to oil on the survival and development rate of the estuarine killifish *Fundulus heteroclitus*. *Mar. Biol.* 51:101-109.
Longwell, A. C. 1977. A genetic look at fish eggs and oil. *Oceanus* 20:46-58.
Mahoney, B. M., and H. H. Haskin. 1980. Effects of petroleum hydrocarbons on the growth of phytoplankton recognized as food forms for the eastern oyster, *Crassostrea virginica* Gmelin. *Environ. Pollut.* 22:123-132.
Mathias, J. A. 1977. The effect of oil on seedlings of the pioneer mangrove, *Avicennia intermedia*, in Malaysia. *Mar. Res. Indones.* 18:17.
McCain, B. B., H. O. Hodgkins, W. D. Gronlund, J. W. Hawkes, D. W. Brown, M. S. Myers, and J. H. Vandermeulen. 1978. Bioavailability of crude oil from experimentally oiled sediments to English sole (*Parophrys vetulus*), and pathological consequences. *J. Fish. Res. Bd. Can.* 35:657-664.
Mecklenberg, T. A., S. D. Rice, and J. F. Karinen. 1977. Molting and survival of king crab (*Paralithodes camtschatica*) and coonstripe shrimp (*Pandalus hypsinotus*) larvae exposed to Cook Inlet crude oil water soluble fraction. In *Fate and effects of petroleum hydrocarbons in marine ecosystems and organisms*, ed. D. A. Wolf, 221-228. New York: Pergamon Press.
Miller, D. S., D. B. Peakall, and W. B. Kinter. 1978. Ingestion of crude oil: Sublethal effects in Herring Gull chicks. *Science* 199:315-317.
Minchew, C. W. D., and J. D. Yarbrough. 1977. The occurrence of fin rot in mullet (*Mugil cephalus*) associated with crude oil contamination of an estuarine pond-ecosystem. *J. Fish. Biol.* 10:319-323.
Moles, A. 1980. Sensitivity of parasitized coho salmon fry to crude oil, toluene and naphthalene. *Trans. Am. Fish. Soc.* 109:293-297.
Moles, D. A., and S. D. Rice. 1983. Effects of crude oil and naphthalene on growth, caloric content and fat content of pink salmon juveniles in seawater. *Trans. Am. Fish. Soc.* 112:205-211.
Moles, A. S., Bates, S. D. Rice, and S. Korn. 1981. Reduced growth of coho salmon fry exposed to two petroleum components, toluene and naphthalene in fresh water. *Trans. Am. Fish. Soc.* 110:430-436.
National Research Council. 1985. *Oil in the sea: Inputs, fates and effects*. Washington, DC: National Academy Press.
National Research Council. 1989. *Using oil spill dispersants on the sea*. Washington, DC: National Academy Press.
Neff, J. M., J. W. Anderson, B. A. Cox, R. B. Laughlin, Jr., S. I. Rossi, and H. E. Tatum. 1976. Effects of petroleum on survival, respiration and growth in marine animals. In *Sources, effects and sinks of hydrocarbons in the marine environment*, 516-539. Washington, DC: American Institute of Biological Sciences.
Ott, F. S., R. P. Harris, and S. C. M. O'Hara. 1978. Acute and sublethal toxicity of naphthalene and three methylated derivatives to the estuarine copepod, *Eurytemora affinis*. *Mar. Environ. Res.* 1:49-58.
Page, D. S., E. S. Gilfillan, J. C. Foster, E. Pendergast, L. Gonzales, and D. Vallas. 1985a. Compositional changes in dispersed crude oil in the water column during a nearshore test spill. In *Proceedings, 1985 Oil Spill Conference*, 521-530. Washington, DC: American Petroleum Institute.
Page, D. S., E. S. Gilfillan, J. C. Foster, J. R. Hotham, and L. Gonzales. 1985b. Mangrove leaf tissue sodium and potassium ion concentrations as sublethal indicators of oil stress in mangrove trees. In *Proceedings, 1985 Oil Spill Conference*, 391-393. Washington, DC: American Petroleum Institute.
Peakall, D. B., D. J. Hallet, J. R. Bend, G. L. Foureman, and D. S. Miller. 1982. Toxicity of Prudhoe Bay crude oil and its aromatic fraction to nesting Herring Gulls. *Environ. Res.* 27:206-215.
Peakall, D. B., A. Jeffrey, and D. S. Miller. 1985. Weight loss of Herring Gulls exposed to oil and oil emulsion. *Ambio* 14:108-110.
Peakall, D. B., P. G. Wells, and D. Mackay. 1987. A hazard assessment of chemically dispersed oil spills and seabirds. *Mar. Environ. Res.* 22:91-106.
Prouse, N. J., and D. C. Gordon. 1976. Interactions between the deposit feeding polychaete *Arenicola marina* and oiled sediment. In *Sources, effects and sinks of hydrocarbons in the marine environment, 407-422.* Washington, DC.: American Institute of Biological Sciences.
Pulich, W. M., K. Winters, and C. Van Baalen. 1974. Effects of a No. 2 fuel oil and two crude oils on the growth and photosynthesis of microalgae. *Mar. Biol.* 28:87-94.
Renzoni, A. 1973. Influence of crude oil, derivatives and dispersants on larvae. *Mar. Pollut. Bull.* 4:9-13.
Rice, S. D. 1985. Effects of oil on fish. In *Petroleum effects in the arctic environment*, ed. F. R. Englehardt, 157-182. London: Elsevier Applied Science Publishers.
Rice, S. D., D. A. Moles, and J. W. Short. 1975. The effect of Prudhoe Bay crude oil on survival and growth of eggs, alevins and fry of pink salmon, *Oncorhynchus gorbuscha*. In *Proceedings, 1975 Oil Spill Conference*, 503-507. Washington, DC: American Petroleum Institute.
Rice, S. D., J. W. Short, C. C. Broderson, T. A. Mecklenberg, D. A. Moles, C. J. Misch, D. L. Cheatham, and J. F. Karinen. 1976. *Acute toxicity and uptake-depuration studies with Cook Inlet crude oil, Prudhoe Bay crude oil, No. 2 fuel oil and several subarctic marine organisms*. Progress report to Northwest Fisheries Center, Auke Bay Fisheries Laboratory, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Auke Bay, AK.
Rice, S. D., D. A. Moles, T. Taylor, and J. F. Karinen. 1979. Sensitivity of 39 Alaskan species to Cook Inlet crude oil and No. 2 fuel oil. In *Proceedings, 1979 Oil Spill Conference*, 549-554. Washington, DC: American Petroleum Institute.
Robertson, M. J., and W. B. Robertson. 1982. *Occurrence and effects of chronic low-level oil contamination in a population of Sooty Terns (Sterna fuscata)*. Unpubl. manuscript.

Roesijadi, G., and J. W. Anderson. 1979. Condition index and free amino acid content of *Macoma iniquinata* exposed to oil-contaminated marine sediments. In *Marine pollution: Functional responses*, ed. W. B. Vernberg, A. Calabrese, F. Thurberg, and F. J. Vernberg, 69-83. New York: Academic Press.
Rogerson, A., and J. Berger. 1981. The toxicity of the dispersant Corexit 9527 and oil/dispersant mixtures to ciliate protozoans. *Chemosphere* 10:33-39.
Rossi, S., and J. W. Anderson. 1978. Effects of no. 2 fuel oil water soluble fractions on growth and reproduction in *Neanthes arenaceodentata*. *Water, Air, Soil Pollut.* 9:155-170.
Scholten, M., and J. Kuiper. 1987. The effects of oil and chemically dispersed oil on natural phytoplankton communities. In *Proceedings, 1987 Oil Spill Conference*, 255-257. Washington, DC: American Petroleum Institute.
Sekerek, A., and M. Foy. 1978. Acute lethal toxicity of Corexit 9527/Prudhoe Bay crude oil mixtures to selected arctic invertebrates. *Spill Technol. Newsletter* 3:37-41.
Sharp, J. R., K. W. Fucik, and J. M. Neff. 1979. Physiological basis of differential sensitivity of fish embryonic stages to oil pollution (*Fundulus heteroclitus*). In *Marine pollution: Functional responses*, ed. W. B. Vernberg, A. Calabrese, F. P. Thurberg, and F. J. Vernberg, 85-108. New York: Academic Press.
Shuba, P. J., and A. J. Heikamp. 1989. Toxicity tests on biological species indigenous to the Gulf of Mexico. In *Proceedings, 1989 Oil Spill Conference*, 309-316. Washington, DC: American Petroleum Institute.
Smith, R. L., and J. A. Cameron. 1979. Effect of water soluble fraction of Prudhoe Bay crude oil on embryonic development of Pacific herring. *Trans. Am. Fish. Soc.* 108:70-75.
Smith, T. G., J. R. Geraci, and D. J. St. Aubin. 1983. Reaction of bottlenose dolphins, Tursiops truncata, to a controlled oil spill. *Can. J. Fish. Aquat. Sci.* 40:1522-1525.
Steele, R. L. 1977. Effects of certain petroleum products on reproduction and growth of zygotes and juvenile stages of the alga, *Fucus edentatus* (Phaeophyceae: Fucales). In *Fate and effects of petroleum hydrocarbons in marine organisms and ecosystems*, ed. D. A. Wolfe, 182-191. New York: Pergamon Press.
Szaro, R. C. 1977. Effects of petroleum on birds. In *Proceedings, 42nd North American Wildlife Conference*, 374-381. Washington, DC: American Petroleum Institute.
Szaro, R. C., and P. H. Albers. 1977. Effects of external application of no. 2 fuel oil on common eider eggs. In *Fate and effects of petroleum hydrocarbons in marine ecosystems and organisms*, ed. D. A. Wolf, 164-167. New York: Pergamon Press.
Tatum, H. E., B. A. Cox, and J. W. Anderson. 1978. The toxicity of oils and petroleum hydrocarbons to estuarine crustaceans. *Estuar. Coast. Mar. Sci.* 6:365-373.
Teas, H. J., E. O. Duerr, and J. R. Wilcox. 1987. Effects of South Louisiana crude oil and dispersants on *Rhizophora* mangroves. *Mar. Pollut. Bull.* 18:122-124.
Thorhaug, A., and J. H. Marcus. 1985. Effects of dispersant and oil on subtropical and tropical seagrasses. In *Proceedings, 1987 Oil Spill Conference*, 497-501. Washington, DC: American Petroleum Institute.
Thorhaug, A., and J. H. Marcus. 1987a. Oil spill clean-up: The effect of three dispersants on three subtropical/tropical seagrasses. *Mar. Pollut. Bull.* 18:124-126.
Thorhaug, A., and J. H. Marcus. 1987b. Preliminary mortality effects of seven dispersants on subtropical/tropical seagrasses. In *Proceedings, 1987 Oil Spill Conference*, 223-224. Washington, DC: American Petroleum Institute.
Thorhaug, A., and J. H. Marcus. 1987c. Effects of seven dispersants on growth of three subtropical/tropical atlantic seagrasses. In *Fate and effects of oil in marine ecosystems*, ed. J. Kuiper and W. J. Van den Brink, 201-205. Dordrecht: Martinus Nijhoff.
Thorhaug, A., J. Marcus, and F. Booker. 1986. Oil and dispersed oil on subtropical and tropical seagrasses in laboratory studies. *Mar. Pollut. Bull.* 17:357-361.
Tokuda, H. 1979. Fundamental studies on the influence of oil pollution on marine organisms. IV. The toxicity of mixtures of oil products and oil spill emulsifiers to phytoplankton. *Nippon Suisan Gakkaishi* 45:1289-1291.
Topinka, J. A., and L. R. Tucker. 1981. Long term oil contamination of fucoid macroalgae following the *Amoco Cadiz* oil spill. In *Amoco Cadiz: Fates and effects of the oil spill*, 393-403. Paris: Centre Nationale Pour L'Exploitation des Oceans.
Trudel, B. K. 1978. EFfect of crude oil and crude oil/Corexit 9527 suspensions on carbon fixation by natural marine phytoplankton community. *Spill Technol. Newsletter* 3:56-64.
Vandermeulen, J. H., D. E. Buckley, E. M. Levey, B. F. Long, P. McLaren, and P. G. Wells. 1978. Immediate impact of *Amoco Cadiz* environmental oiling: Oil behavior and burial and biological aspects. In *Amoco Cadiz: Preliminary observations of the oil spill impact on the marine environment*, ed. G. Conan, D'Ozouville and M. Marchand, 159-173. Actes de Colloques 6. Paris: Centre Nationale Pour L'Exploitation des Oceans.
Varanasi, U., W. L. Reichert, and J. E. Stein. 1989a. ^{32}P postlabeling analysis of DNA adducts in liver of wild English sole (*Parophrys vetulus*) and winter flounder (*Pseudopleuronecies americanus*). *Cancer Res.* 49:1171-1177.
Varanasi, U., W. L. Reichert, B. Le Eberhart, and J. E. Stein. 1989b. Formation and persistence of benzo(a)pyrene diolepoxide adducts in liver of English sole (*Parophrys vetulus*). *Chem. Biol. Interact.* 69:203-216.
Vargo, G. A., M. Hutchins, and G. Almquist. 1982. The effect of low, chronic levels of no. 2 fuel oil on natural phytoplankton assemblages in microcosms: I. Species composition and seasonal succession. *Mar. Environ. Res.* 6:245-264.
Vargo, S., P. Lutz, D. Odell, E. Van Vleet, and G. Bossart. 1986. *Effects of oil on marine turtles*. Contract No. 14-12-0001-30063. Vienna, VA: U.S. Department of the Interior, Minerals Management Service.
Vuorinen, P., and M. B. Axell. 1980. Effects of the water soluble fraction of crude oil on herring eggs and pike fry. I.C.E.S., C.M. 1980/E:30.
Wells, P. G. 1972. Influence of Venezuelan crude oil on lobster larvae. *Mar. Pollut. Bull.* 3:105-106.
Wells, P. G., and J. A. Percy. 1985. Effects of oil on arctic invertebrates. In *Petroleum effects in the arctic environment*, ed. F. R. Englehardt, 101-156. London: Elsevier Applied Science Publishers.
Wells, P. G., and J. B. Sprague. 1976. Effects of crude oil on American lobster (*Homarus americanus*) larvae in the laboratory. *J. Fish. Res. Bd. Can.* 33:1604-1614.
Winters, K., C. Van Baalen, and J. A. C. Nicol. 1977. Water soluble extractives from petroleum oils: Chemical characterization and effects on microalgae and marine animals. *Rapp. P.-V. Réun. CIEM* 171:166-174.
Woodward, D. F., P. M. Mehrle, Jr., and W. L. Mauck. 1981. Accumulation and sublethal effects of a Wyoming crude oil in cutthroat trout. *Trans. Am. Fish. Soc.* 110:437-445.
Wyers, S. C., H. R. Frith, R. E. Dodge, S. R. Smith, A. H. Knap, and T. D. Sleeter. 1986. Behavioral effects of chemically dispersed oil and subsequent recovery in *Diploria strigosa* (Dana). *Mar. Ecol.* 7:23-42.

CHAPTER 15
THE SENSITIVITY OF SOUTH FLORIDA ENVIRONMENTS TO OIL SPILLS AND DISPERSANTS

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INTRODUCTION

South Florida's precious coastal and nearshore habitats are stressed by encroaching urban, agricultural, and industrial development. After years of exploitation by developers and agriculturalists, there is not much left of natural Florida. Accordingly, many Floridians view the prospect of offshore oil and gas operations as one more possible source of environmental degradation. The foremost public concern is that a major oil spill in South Florida could seriously damage large areas of the remaining natural environment.

In recent months, much attention has been drawn to and much debate has focused on the potential effects of oil spills on the natural ecosystems of South Florida. The general public and several identifiable groups of Floridians are concerned about the potential damage to coastal habitats from offshore gas and oil operations and from tanker spills. South Florida entrepreneurs, who own tourist-oriented businesses, are concerned about the effects that the images of a large oil spill in this area would have on the vacation plans of their potential customers. Florida fishermen are worried about the direct effects of a spill on the already limited stocks of many commercially important species. Ecologists, naturalists, and conservationists are apprehensive about the long-term effects that a spill might have on the diversity and abundance of the biota inhabiting South Florida's complex coastlines.

Much of the public concern about oil spills stems from large, well-known incidents such as the 1969 Santa Barbara Channel blowout (Straughan 1971), the 1979 *Ixtoc I* blowout in Mexican waters (Atwood and Ferguson 1982), and the 1989 *Exxon Valdez* tanker spill in Prince William Sound, Alaska (National Response Team 1989). The *Exxon Valdez* spill is of particular interest because it has highlighted problems with oil spill response, including inadequate contingency planning, general complacency due to the large number of accident-free shipments of oil through the area, and primitive oil spill cleanup procedures and technologies (National Response Team 1989).

The purpose of this chapter is to evaluate the sensitivity and vulnerability of South Florida's coastal habitats, based on information that is available about effects of oil spills on similar ecosystems and communities in other areas. After our evaluation of the potential hazards of oil spills on the typical community types found in South Florida, we will then consider the effects that a large spill might have on each of the major geographically and ecologically distinct subdivisions of the South Florida area. After that, we will address the need for further research which might fill in some of the gaps in our knowledge about the long-term effects of oil spills on tropical and subtropical marine communities.

In the following discussions of oil spill effects on shallow-water and coastal communities typical of South Florida, attention will be focused on how damage at lower levels of ecological organization, i.e., individuals and populations, affects community structure and function. This information could be useful in determining the potential effects of oil spills if it were incorporated into ecosystem models, such as those presented by Schomer and Drew (1982) for each of the major natural subdivisions ("ecological zones") of the coastal region of South Florida (e.g., **Figure 15.1**). The predictive value of energy- and materials-flow models would be greatly increased if we had a better understanding of how oiling affects the species, populations, and assemblages that inhabit each of the ecosystem subcomponents.

VULNERABILITY AND SENSITIVITY TO SPILLED OIL

The concepts of habitat vulnerability and sensitivity to oiling are easily defined[1] (as in Vandermeulen and Gilfillan 1984), but the actual ranking of habitat types and species on scales based on these definitions is dependent on a wide range of factors that are not easy to predict. The vulnerability of a habitat type depends on its geographic location and its position in the intertidal or subtidal zones, and thus its likelihood of coming into contact with petroleum hydrocarbons (PHC). Habitat vulnerability is increased in quiet lagoonal backwaters where flushing is poor and in areas adjacent to turbulent surf zones on open coastlines where oil may be mixed into emulsions within water (The International Tanker Owners Pollution Federation, Ltd. 1986; Marshall and Batista in

[1] As used here, "vulnerability" is the likelihood of coming into contact with oil or hydrocarbons, and "sensitivity" is the degree of damage an organism, population, community, or system is likely to incur.

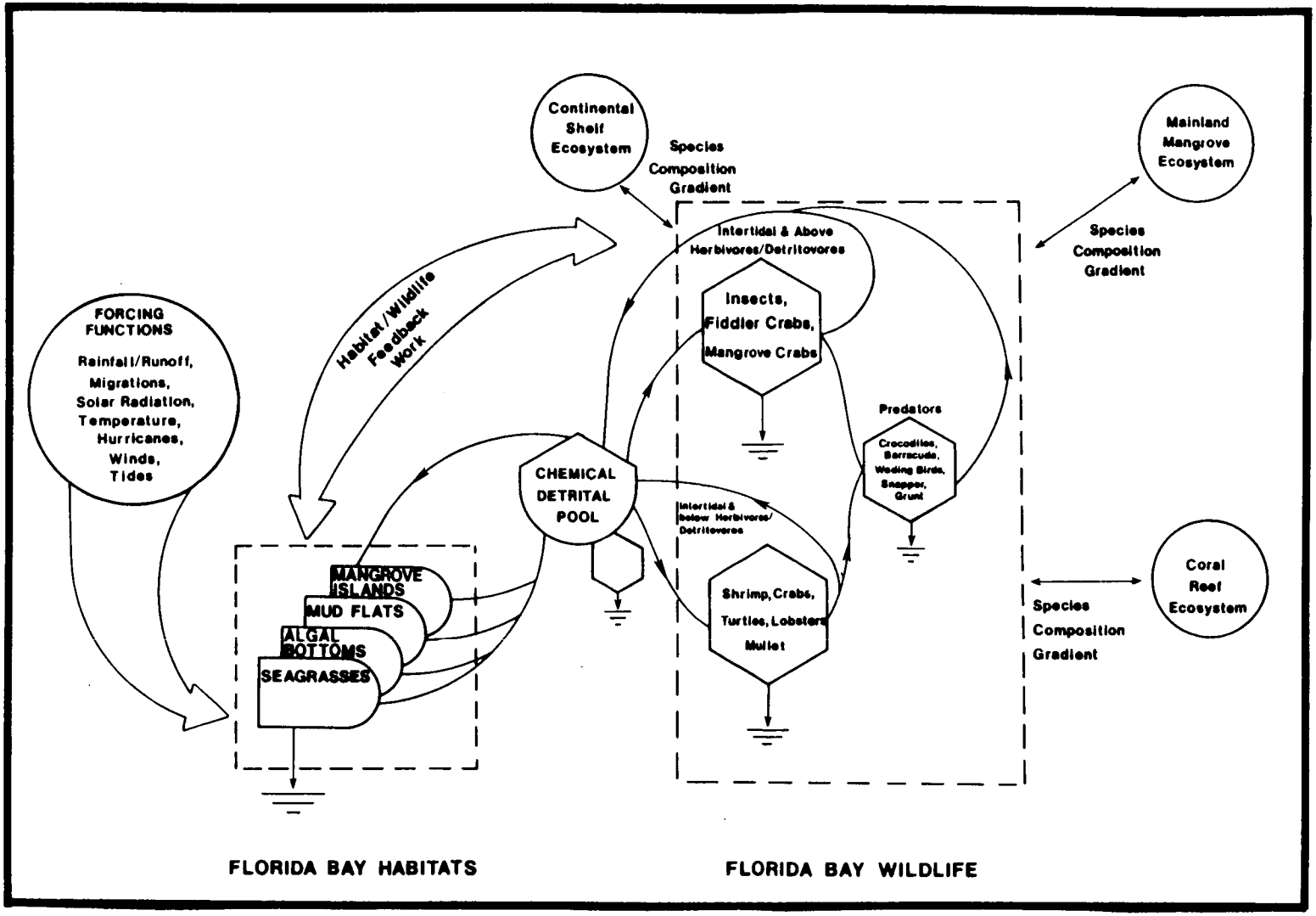


Figure 15.1. Summary diagram of energy flow through the Florida Bay/mangrove island ecosystem (From: Schomer and Drew 1982).

prep.). Floating oil may also combine with suspended particles, thereby increasing the oil's specific gravity to the point at which it sinks in seawater. When this happens, subtidal environments become vulnerable. Marine, shallow-water habitats and their resident species should be less vulnerable in offshore and open coastal areas with strong currents and high flushing rates, during calm weather.

Sensitivity is determined by the species mix of structural and structure-inhabiting species and the degree of toxic damage or effect that each species is likely to incur. It has been concluded, based on an extensive survey of the available literature, that all organisms are sensitive to oiling and that no known organism can actively exclude hydrocarbons from its tissues (National Research Council [NRC] 1985). Structural species such as the tree species that are commonly found in mangrove forests, the dense mats of algae and sessile animal species on mangrove prop roots, the algae and sessile animals of reef flats, the coral species that form the living framework of a coral reef, and the seagrass and algal species that define seagrass meadows are all variously vulnerable and sensitive to spilled oil. Single oil spills, such as the Bahia las Minas spill in Panama (Jackson et al. 1989), have killed mangrove trees, mangrove prop root fauna, corals, and seagrasses.

PHYSICAL AND CHEMICAL PROPERTIES OF OIL

The physical and chemical properties of spilled oil play a large role in determining habitat vulnerability and sensitivity. Weathering of oils includes a number of physical and chemical changes (see **Chapter 3**). The processes involved in weathering act simultaneously, but their relative importance changes during the lifetime of an oil slick (The International Tanker Owners Pollution Federation, Ltd. 1986). Weathering processes include spreading, evaporation, dispersion, emulsification, dissolution, oxidation, sedimentation, and biodegradation. An understanding of the way in which weathering processes affect habitat vulnerability and species sensitivity is essential in predicting the effects of oil spills on ecological communities. This need is usually not recognized by the ecologists who do biological impact studies or by petroleum chemists who are concerned only with the weathering process with respect to changes in oil composition.

Odum (1972) modeled oil spilled into a generalized marine ecosystem in an attempt to show the fate of oil as a function of time (**Figure 15.2**). His model predicted that large amounts of oil would dissolve in seawater, and that other fractions would be deposited in the sediments. Benthic communities could come into contact with oil by these two routes. The biological fate and effects of the oil fractions considered in Odum's model are complex and vary with trophic levels (Ganning et al. 1984). These interactions need to be considered in all oil spill-related research. Most recent research, including field experiments and post-spill followup studies, that is applicable to the South Florida area cannot be used to accurately predict the effects of a large oil spill in an area containing complex and interacting ecosystems. This should be evident from the ensuing discussion.

STUDIES OF EXPERIMENTAL AND ACCIDENTAL OIL SPILLS

There have been numerous laboratory studies of oil effects on corals (Eisler 1975; Knap et al. 1983; Dodge et al. 1984; Knap et al. 1985; Knap 1987), mangroves (Getter et al. 1983; Getter and Ballou 1985; Lai and Feng 1985; Teas et al. 1987), and seagrasses (Thorhaug and Marcus 1985, 1987a,b,c; Thorhaug et al. 1986). These are generally viewed as low in realism; that is, they provide limited information upon which to judge the ways in which oil and dispersants might affect complex communities under natural conditions (Burns and Knap 1989; Jackson et al. 1989; but see **Chapter 14** and Vandermeulen and Gilfillan 1984 for a different point of view).

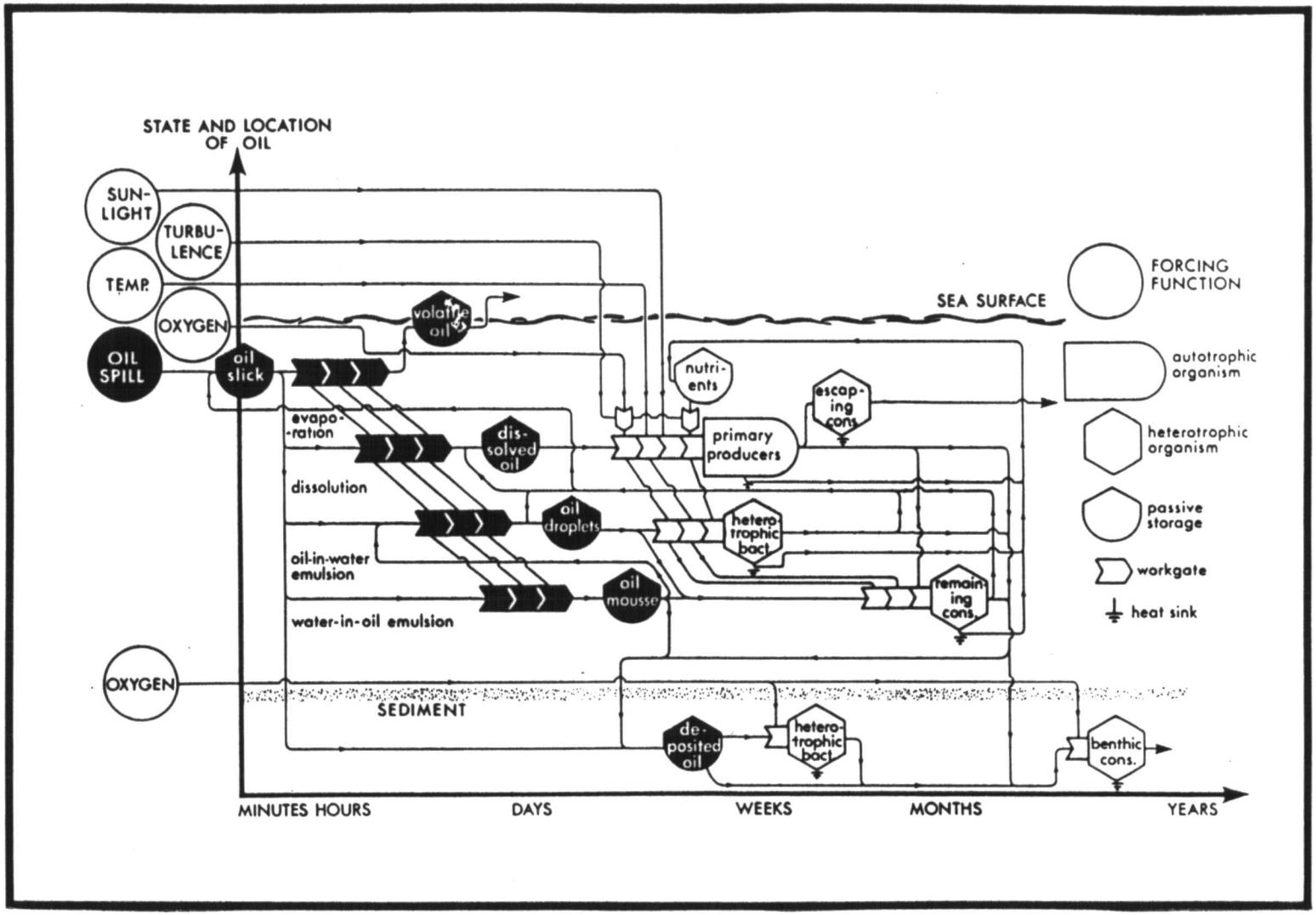


Figure 15.2. Change in state and location of oil in pelagic, intertidal, and subtidal habitats with time (From: Ganning et al. 1984).

Actual field experiments involving oil and dispersant usage are few in number. Major field experiments have typically focused on a single habitat type and have ignored potential effects on adjacent habitats. Lai and Feng (1985) dosed mangroves in Malaysia with various oils and dispersant combinations, with the finding that oil, whether dispersed or not, was very toxic to mangroves (*Avicennia*) in static or semi-static laboratory conditions. Toxicity in the field was lower due to tidal flushing. Le Gore et al. (1983) treated coral reefs in the Middle East with oil and dispersants, and found little effect on survival, growth, and recruitment. The experiment, however, was highly unrealistic in that corals were exposed to oil and/or dispersant for very short periods (either 1-day or 5-day exposures). In Panama, corals in shallow (<6 m) water have been repeatedly exposed to oil, in various stages of weathering, from the Bahia las Minas oil spill for at least 2.5 years (Guzman et al. in review).

The American Petroleum Institute (API) dispersant project (Ballou et al. 1987) in the Laguna de Chiriqui, Panama has been the most comprehensive field experiment to date in that oil effects on mangroves, seagrasses, coral reefs, and the other fauna and flora of each habitat type were monitored together in pre- and post-treatment sampling programs. The project's chief purpose was to obtain experimental data to determine if the use of chemical dispersants would reduce or exacerbate adverse effects of oil spills upon sensitive tropical environments. The experimental approach was intended to simulate a "severe, but realistic, worst-case scenario" of two large spills of fresh crude oil in nearshore waters--one treated with chemical dispersants and the other left untreated. The combined experiences of the authors with oil spills were used to determine oil amounts and dispersant application rates. They agreed that the experimental design resulted in "strong tests" of the potential effects of both oil and dispersant-treated oil. The dispersant-treated oil experiment represented procedures that are not recommended, in that dispersant-use strategies call for treatment of oil slicks in deep water only. (This recommendation is not always followed; for example, dispersants were used to treat oil slicks located just offshore from the Bahia las Minas, Panama, Refineria Nacional-Texaco oil refinery in an area of shallow coral reefs, seagrass meadows, and tropical mangrove forests [Cubit et al. 1987]).

The API project used Prudhoe crude oil and a commercial nonionic glycol ether-based dispersant concentrate. The experiment was directly applicable to the experimental site because Prudhoe crude oil is pumped across Panama from tankers in Puerto Armuelles (on the Pacific coast) to the Laguna de Chiriqui (on the Atlantic coast) where it is reloaded into tankers. A recent spill of crude oil (190,000 to 240,000 L during November 1989) into the Laguna de Chiriqui from pipelines owned by Petro-terminal de Panama, S.A. oiled mangroves and threatened seagrass meadows and subtidal reef corals (H. Guzman, Smithsonian Tropical Research Institute, pers. comm. 1989 to M. Marshall).

Oil and oil/dispersant application rates in the API study were predetermined to yield concentrations of 50 ppm. The oil-only treatment defoliated and killed mangrove trees; reduced the abundance of mangrove-associated marine snails; and altered the vertical distribution of tree snails. Oysters that were attached to mangrove roots survived, with tissue hydrocarbon concentrations of 678 ppm. After the dispersed-oil treatment, at a separate site, no measurable effects were detected on adult trees, but short-term survival and growth of juvenile mangroves were reduced compared to pretreatment levels. Marine snail abundances were reduced by about 50% after treatment, with recovery to pretreatment levels occurring after one year. Mangrove oysters also survived the dispersed-oil treatment despite high concentrations (506 ppm) of hydrocarbons in their tissues.

Coral cover and the abundances of coral associated fauna and flora in the dispersed oil treatment declined abruptly following the release of the oil-dispersant mixture. Coral cover declined less rapidly in the oil-only treatment. Dispersant-treated oil slowed growth rates for two coral species, but did not alter growth rates for two other species. Undispersed oil did not affect coral growth rates. Seagrass areas treated with dispersed and undispersed crude oil showed decreased seagrass densities. Dispersed-oil treatment seagrass densities returned to higher than pretreatment densities, but oil-only treated seagrass remained lower than pretreatment levels. Sea urchin abundance in seagrass meadows decreased rapidly in the dispersant-treated site and declined more slowly in the oil-treated site.

Ballou et al. (1987) discussed treatment options developed from the API study experimental results. Their discussion suggests that although dispersants do protect mangroves, they should not be used over shallow-water coral and seagrass communities.

The preliminary results of the Bahia las Minas oil spill study (Jackson et al. 1989) suggest that other factors not considered in the API study, i.e., oil-in-water emulsions formed in high surf zones and the trapping of huge amounts of oil in mangrove forest sediments, may greatly increase the damage done to subtidal benthic communities by crude oil. Toxic volatile compounds in oil, which normally evaporate rapidly, can be transported over long distances in emulsions (NRC 1985). Suspended sediments may adhere to oil droplets in emulsions and cause them to sink by increasing their combined specific gravity. Thus, sinking oil with many highly toxic volatile components still present may make contact with subtidal organisms. The results of the API experimental study might be applicable only to spills which occur in protected lagoons, or on shallow open coastlines during calm spells, when and where emulsions are not likely to be formed.

Oil concentrations in the API study may have been realistic, but the amount of oil used could not possibly have the same effect as a large spill. Tens of thousands of liters of oil can be trapped inside, and only slowly released from, heavily oiled mangrove forests. After a major oil spill in the tropics or subtropics, seagrasses and coral reefs can be re-oiled many times whenever weathered oil washes out of oiled mangrove forests. Oil buried in anoxic mangrove sediments may weather at a very slow rate. Judging from the differing results of the API experimental oil spill study with one year of followup studies (Ballou et al. 1987), and studies of the accidental Bahia las Minas spill (Burns and Knap 1989; Jackson et al. 1989; Cubit and Burgett in press; Guzman et al. in review; Marshall and Batista in prep.), it would be very difficult to design and implement realistic field experiments. A realistic design for a tropical oil spill would necessitate the application of oil to corals and seagrasses over a period of many months or even years (Burns and Knap 1989; Guzman et al. in review).

EFFECTS ON SELECTED ENVIRONMENTS AND BIOTA

A number of authors have reviewed the literature on the effects of spilled oil on tropical coastal systems including mangrove forests, coral reefs, seagrass meadows, salt marshes, and rocky intertidal habitats (Getter et al. 1981; Baker 1982; Lewis 1983; Ganning et al. 1984; Vandermeulen and Gilfillan 1984; NRC 1985). Other spills have occurred since the publication dates of these reviews, and we have added this information to tables, taken from the NRC (1985) summary and Loya and Rinkevich (1980), for mangrove forests and coral reefs, respectively. A table which summarizes oil spill effects on seagrass communities is included in this section, because several highly informative studies on these important ecosystems warrant the effort.

Mangrove Forests

Mangroves are generally the most vulnerable and may be the most sensitive of coastal habitat types in Florida waters and throughout the tropics. (Defoliated and dead mangrove trees are also more noticeable than are the more "subtle," but equally lethal, effects of oil on subtidal organisms). This has been repeatedly demonstrated by the oil spills summarized in **Table 15.1**. Of the 14 cases summarized in **Table 15.1**, substantial numbers of mangroves were reported to have been killed in 10 cases; trees were reported to have been defoliated and recovered in one case, and to have been little affected in only two cases. Damages to mangroves are under study in the remaining case. More rigorous and longer-term followup studies may have produced differing results in the spills listed in **Table 15.1** in which little effect was noted. Studies of oil spill effects on mangrove forests range from anecdotal accounts (i.e., Diaz-Piferrer 1962) to more thorough studies of both initial effects and long-term recovery processes (i.e., studies of the *Zoe Colocotroni* oil spill site in Puerto Rico [Nadeau and Bergquist 1977; Page et al. 1979; Gilfillan et al. 1981]).

Mangroves, including adult trees, seedlings, and propagules, are extremely sensitive to oiling (e.g., Teas et al. 1989). Mangroves are found in the intertidal zone, and their prop roots and pneumatophores (specialized structures which allow the trees to grow in the anoxic and highly saline sediments that are typical of the forest floor [Odum et al. 1982]) are commonly heavily coated by spilled oil. A coating of oil on these structures may disrupt oxygen transport to underground roots. Critical concentrations necessary for crude oil spills to cause extensive damage range from 100 to 200 mL/m^2 of sediment surface (Odum and Johannes 1975). Defoliation and death of oiled trees are the most obvious signs of their high sensitivity to big doses of oil. Many sublethal effects have also been detected; these include stunting of trees and propagules, lenticel expansion, root mortality, and various types of leaf deformities (Getter et al. 1981).

In a recent study of the uptake and effects of petroleum hydrocarbons on the red mangrove *Rhizophora mangle*, Thomas (1987) experimentally subjected reproductively mature trees to varying concentrations (100, 375, and 650 gm/m^2) of mineral, lubricating, and crude oils representing different levels of refinement. Thomas demonstrated the selective uptake (in juvenile and mature leaves, and twigs) of a variety of hydrocarbons, mainly the aromatics, and showed that the effects were statistically related to the specific composition of the oil, reflecting the degree of refinement, or viscosity, the treatment concentration, and the duration of exposure. The deleterious effects on the mangroves were attributed to the toxicity of the aromatic fraction as opposed to the aliphatic fractions which were also assayed. Thomas' (1987) set of laboratory experimental results contrasts with the field experiments reported by Ballou et al. (1987), whose group did not report any significant uptake of hydrocarbons in mangrove leaf material following an experimental controlled spill in Panama. A principal conclusion in the Thomas study is that the aromatics are taken up more easily than aliphatics, and that the total uptake of aromatics is proportional to their concentration in the oil which is a function of the level of refinement. Thus, uptake by mangroves of aromatics from crude oil is greatest because of its relatively high concentration of aromatics. Mineral or lubricating oils are refined products and have lower aromatic concentrations.

The many animals that inhabit mangrove forest floors and/or mangrove prop root habitats are also vulnerable due to the intertidal and protected location of their environment. They are sensitive to the toxic effects or smothering properties of oil, to the loss of mangrove habitat, to decreased supplies of mangrove leaf litter and detritus, and to changes in the physical properties (e.g., temperature) of the mangrove forest floor following the death of large expanses of forest.

Table 15.1. Effects of oil spills on mangroves (Adapted from: National Research Council 1985).

Spill	Amount Spilled	Mangrove Species	Reported Effects	Reference
1962, ARGEA PRIMA, Guanica, Puerto Rico	10.68 million liters	Unidentified	Virtual destruction of habitat	Diaz-Piferrer (1962)
1968, WITWATER, near Galeta Island, Panama	3.18 million liters diesel oil and Bunker C	*Rhizophora mangle* and *Avicennia* sp.	Death of young mangroves, loss of sessile animals and algae on prop roots (loss visible 66 months after spill)	Rutzler and Sterrer (1970), Birkeland et al. (1976)
1970 pipeline break, Tarut Bay, Saudi Arabia	At least 15.9 million liters light crude	*A. marina*	Defoliation, but many trees survived	Spooner (1970)
1971, SANTA AUGUSTA, St. Croix, U.S. Virgin Islands	12.5 million liters crude	*R. mangle*	5 ha completely destroyed; little or no recolonization after 7 yr	Lewis (1979a,b), Lewis and Haines (1980)
1973, ZOE COLOCOTRONI, Cabo Rojo, Puerto Rico	5.34 million liters Venezuelan crude	*R. mangle* and *A. germinans*	Death of adult trees (red and black) over 1.0 to 2.7 ha area within 3 yr	Tosterson et al. (1977), Nadeau and Bergquist (1977), Page et al. (1979), Gilfillan et al. (1981)
1975, GARBIS, Florida Keys	0.24 to 0.48 million liters crude	*R. mangle* and *A. germinans* (*nitida*)	Death of young red mangrove seedlings and some dwarf black mangroves	Chan (1976, 1977), VAST/TRC (1976)
1975, SHOWA MARU, Indonesia	8.6 million liters Arabian Light, Berri, and Murban crude	*Sonneratia* sp. and *Rhizophora* sp.	Unquantified number of dead trees, both species; greatest effects in sheltered bays; few crabs and molluscs associated with oiled sediments afterward	Baker (1981), Baker et al. (1981)
1976 pipeline rupture, Corpus Christi, TX	60,000 liters crude	*A. germinans*	Mangroves burned to remove oiled, uncleaned trees; recovered after minor defoliation	Holt et al. (1978)
1976, ST. PETER, Colombia/Ecuador	38.71 million liters cargo; unknown quantity spilled	*Rhizophora* sp. and *Avicennia* sp.	No noticeable long-term effects; temporary decline in fishery and clam harvesting	Jernelov et al. (1976), Jernelov and Linden (1980), Hayes (1977)
1977 unidentified vessel, Guayanillu Bay, Puerto Rico	159,000 liters Venezuelan crude	*R. mangle*	Damage to mangrove root community; trees survived	Lopez (1978)
1978, HOWARD STAR, Tampa, FL	0.15 million liters, 20% diesel and 80% Bunker C	*R. mangle*, *A. germinans*, and *Laguncularia racemosa*	Mortalities in molluscs, polychaetes, and all mangrove species; root abnormalities	Gundlach et al. (1979a), Getter et al. (1980a), Lewis (1980a,b), Snedaker et al. (1981)
1978 PECK SLIP barge, Puerto Rico	16.65 to 17.41 million liters Bunker C	*R. mangle*	Significantly affected mangrove, crab, mollusc, and epiphyte population	Gundlach et al. (1979b), Robinson (1979)
1980, FUNIWA 5, offshore oil well, Nigeria	31.8 million liters crude	*R. racemosa*, *A. africana*, and *L. racemosa*	Under study	Oil Spill Intelligence Report (1980a,b), Baker (1981), Teas and Gilfillan (unpubl. data)
1986, Refineria Panama, Bahia las Minas, Panama	8.0 million liters	*R. mangle*	Death, defoliation of mangrove trees; mangrove prop root community destroyed	Cubit et al. (1987), Jackson et al. (1989), Teas et al. (1989)

In the 1973 *Zoe Colocotroni* oil spill, both the red mangrove *Rhizophora mangle* and the black mangrove *Avicennia nitida* were defoliated and slowly killed during the three years following the spill. Propagules that sprouted rapidly in the oiled mangrove forests died as their cotyledenous reserves were used up (A. Lugo, Institute of Tropical Forestry, Puerto Rico, pers. comm. to S. Snedaker). Also, in the spill litigation, much confusion surrounded the question of differential mortality, due to an unpredictable interaction between oil and natural hypersalinity (Puerto Rico vs. M/V *Zoe Colocotroni*: see Commonwealth of Puerto Rico... 1973, 1978; Lugo et al. 1981). High levels of sediment PHCs were still present in the soil in the affected areas three years after the spill (Nadeau and Bergquist 1977). A survey of PHC distribution patterns four years after the spill, indicated that *Zoe Colocotroni* oil was still present in the soil but that its characteristics had changed greatly (Page et al. 1979). Damage to the infaunal communities associated with red mangroves (*R. mangle*) was still evident from samples collected during 1978 and 1979 (Gilfillan et al. 1981). Red mangroves had not yet recovered in these areas. However, some evidence of infaunal community recovery was evident in sites where oil concentrations exceeded 80,000 ppm. The authors suggested that the biological activity of this weathered (5 to 6 years post-spill) oil was very low. Capitellid polychaetes, often considered to be opportunistic species and indicators of pollution, were more abundant at the oiled red mangrove stations than at control sites. Amphipoda, which have proven to be sensitive to exposures to oil in other environments (e.g., den Hartog and Jacobs 1980), were present at most reference sites and absent at all oiled sites. These observations suggested that weathered oil retained in the mangrove forests still had an effect on infauna in the forest floor.

Based on (1) a review of 27 oil spills in the Caribbean and Gulf of Mexico (Getter et al. 1980a), (2) a number of independent studies (Odum and Johannes 1975; Chan 1977; Gundlach et al. 1979a,b; Page et al. 1979; Getter at al. 1980b; Hayes et al. 1980; Lugo et al. 1981; Snedaker et al. 1981), and (3) more recent experimental works (Jagtap and Untawale 1980; Getter 1983; Ballou et al. 1987; Thomas 1987), the state of knowledge concerning oil spills in mangroves can be summarized as follows:

- Mangrove mortality is highest among propagules, seedlings, and juvenile trees, presumably due to their proximity to the oil spill surface, and the potential for heavy oiling. However, Lugo et al. (1981) suggested that mangrove seedlings may be more stress-resistant than adult trees, based, in part, on their observations and the physiological differences reported by McMillan (1974).

- The reported rapid mortality of immature and mature mangrove trees following a spill is probably due to mechanical suffocation and the cessation of gas exchange associated with the rhizosphere. This is, however, somewhat equivocal because in a laboratory experiment using fresh pneumatophores from *A. germinans*, nitrogen gas (the major constituent of the atmosphere) was still able to be transported through the treatment oil film covering the test pneumatophores (M. Brown, Rosenstiel School of Marine and Atmospheric Science, pers. comm. 1986 to S. Snedaker).

- Both delayed mortality and a delayed expression of stress symptoms may occur over a one- to two-year period following an oil spill for reasons that are not clearly understood, but which may be related to the persistence of toxic aromatic compounds in sediments.

- Mortality and acute damage, as well as long-term chronic stress, can be correlated with the topographic location of the accumulation of oil, and the subsequent effectiveness of tidal flushing of oiled surfaces (**Figure 15.3**). Thus, in Southeast Florida and the Florida Keys, basin forests which are infrequently inundated, and salt pond complexes and dwarf forests which are inundated only seasonally, represent the worst-case habitats with respect to both oil spills and natural cleanup (see also Odum and Johannes 1975).

- Transformation and the continual release of oil and oil fractions from sediments via "bleedwater" (Mackin 1950) into nearshore marine environments occur over a period of years following a spill. This is one topic that has not been adequately researched due to the emphasis placed on acute post-spill consequences.

- Refugee oil in surface slicks and in sedimented oil has the ability to scavenge and concentrate pesticides (Seba and Corcoran 1969; Hartung and Klingler 1970). This chemical scavenging and concentrating process could also result in other kinds of toxic organic compounds being incorporated and retained in refugee oil.

- Although some workers have reported an apparent stimulating effect of oil on mangroves (e.g., Page et al. 1979; Thomas 1987), Thomas argues that any deviation from the normal condition is an indication that the oil interfered with normal growth processes and development patterns (see also Getter 1983).

- The various experimental works that are, at least superficially if not in substance, in conflict with one another prevent drawing specific conclusions about how oil affects mangroves over a range of antecedent and actual spill conditions. In this regard, it seems that the underlying reason for the many conflicting research results and conclusions is that oil-effects-type experiments and observations are highly dependent on, and controlled by, the very specific techniques and procedures.

In summary, it can be stated that oil adversely affects mangroves and elicit responses ranging from mortality to chronic sublethal stress. Also, the immediate post-spill acute effects may be less consequential than the long-term chronic effects. However, the topic of long-term effects is only beginning to be addressed by the scientific community.

A long-term study of mangroves oiled by the Refineria Nacional oil spill into Bahia las Minas, Panama is underway (N. Duke, mangrove forest scientist-in-charge, Oil Spill Project, Smithsonian Tropical Research Institute, pers. comm. 1989 to M. Marshall). The initial effects of this spill on the mangrove forest, as described in Cubit et al. (1987) and Jackson et al. (1989), included rapid die-offs of oiled red mangroves in riverine and channel habitats (**Photograph 15.1**). Amounts of bare space on submerged mangrove roots, in these same areas, increased greatly as epibiota died (**Table 15.2**). In some cases, formerly submerged roots and their associated prop root communities were lifted out of the water as mangrove limbs straightened in response to the change in loads caused by complete defoliation.

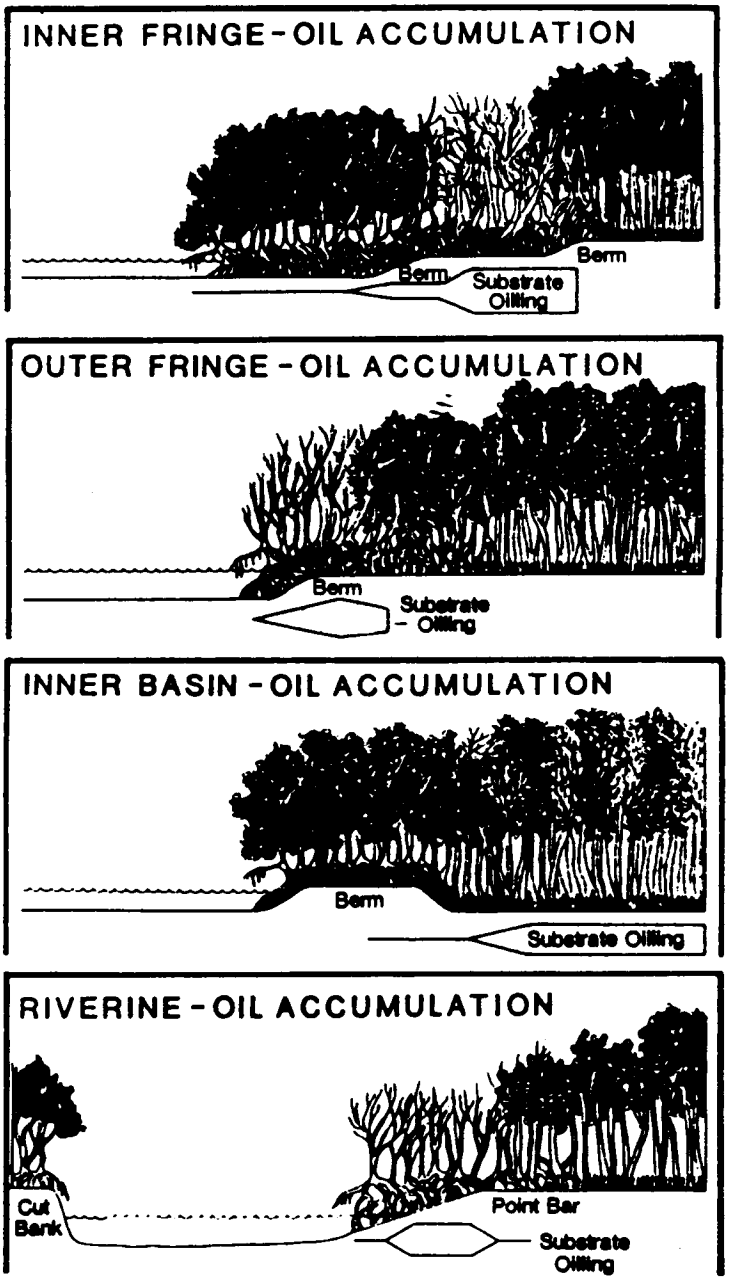


Figure 15.3. Patterns of oil accumulation in different mangrove forest types (From: Snedaker and Getter 1985). Damage to mangroves depends on the pattern of oiling, which differs significantly among mangrove forest types.

Table 15.2. Abundances of major organisms on *Rhizophora* prop roots before and after the Bahia las Minas oil spill in Panama (From: Cubit et al. 1987). N is the number of roots sampled.

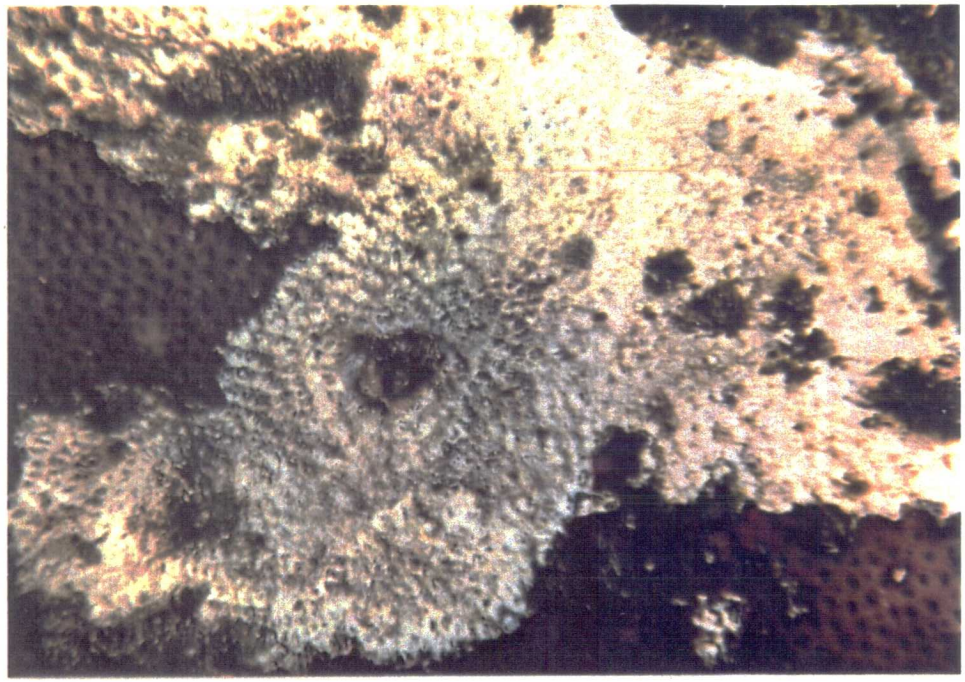
	Percent Coverage				
				Jul 1986	
Habitat and Organism	Sep 1981 Mean (Range)	Jan 1982 Mean (Range)	Jun 1982 Mean (Range)	Unoiled Mean (Range)	Oiled Mean (Range)
Riverine					
Mytilopsis					
Alive	53 (0-86)	47 (0-80)	49 (0-81)	32 (0-90)	0
Dead				1 (0-12)	11 (0-75)
Balanus					
Alive	6 (0-75)	18 (0-90)	2 (0-18)	11 (0-82)	0
Dead				0	3 (0-33)
Algae	7 (0-22)	9 (0-41)	6 (0-14)	10 (0-62)	0
Bare	30 (0-99)	20 (0-95)	40 (7-89)	25 (0-95)	85 (5-100)
N	51	49	25	92	100
Channel					
Crassostrea					
Alive	46 (0-80)	56 (0-96)	62 (0-100)	36 (0-100)	0
Dead				0	21 (0-100)
Isognomon					
Alive	6 (0-20)	5 (0-16)	3 (0-12)	2 (0-16)	6 (0-63)
Dead					2 (0-18)
Mytilopsis	12 (0-30)	11 (0-28)	8 (0-24)	6 (0-82)	4 (0-35)
Branchidontes	2 (0-15)	2 (0-12)	3 (0-12)	6 (0-53)	1 (0-6)
Balanus	15 (0-30)	10 (0-32)	9 (0-36)	6 (0-26)	1 (0-21)
Algae	1 (0-10)	2 (0-8)	3 (0-12)	8 (0-87)	7 (0-71)
Bare	13 (0-100)	10 (0-100)	10 (0-10)	14 (0-81)	6 (0-45)
Diatoms				11 (0-100)	29 (0-100)
N	48	46	25	100	100
Open Coast					
Diatoms	25 (0-100)	5 (0-55)		--	70 (8-100)
Sponges	5 (0-40)	6 (0-54)		--	1 (0-78)
Hydroids					
Alive	5 (0-45)	3 (0-22)		--	2 (0-80)
Dead				--	3 (0-55)
Foliose					
Algae	29 (0-100)	47 (0-100)		--	21 (0-100)
Bare	32 (0-100)	31 (0-100)		--	2 (0-25)
N	50	50			100

Photograph 15.1. Damage to mangroves from the Bahia las Minas spill, Panama. Dead mangrove trees form a band about 8 to 100 m wide marking the area where oil accumulated as it entered the mangrove forest. A band of defoliated trees was apparent within two months after the spill and widened thereafter. Photo by Carl Hansen, Smithsonian Institution Office of Photographic Services.

Photograph 15.2. Underwater view of the coral *Siderastrea radians* partially killed by oil from the Bahia las Minas spill. The central, light-colored area is skeleton devoid of living tissue. Algal colonization has begun on some areas in the dead skeleton patch. Photo by Carl Hansen, Smithsonian Institution Office of Photographic Services.

Photograph 15.3. Oiled intertidal seagrass meadows in Bahia las Minas. Several intertidal seagrass beds died; roots, rhizomes, and leaves washed away, along with the sediments they consolidated. Photo by Carl Hansen, Smithsonian Institution Office of Photographic Services.

Photograph 15.4. Oil on the intertidal reef flat at Punta Galeta. The Smithsonian Tropical Research Institute Galeta Marine Lab can be seen in the background. Photo by Carl Hansen, Smithsonian Institution Office of Photographic Services.



Experimental plantings of seedlings by Getter soon after the Bahia las Minas spill were not successful in oiled areas (Jackson et al. 1989). Teas et al. (1989), however, have reported success in replanting propagules and nursery-grown mangrove seedlings in forest areas killed by the Bahia las Minas spill. *Rhizophora* propagules planted in oiled areas, at three-month intervals after the spill, as a test of reforestation procedures, did not survive at any oiled site until nine months had passed (Teas et al. 1989). Survivorship suddenly increased in propagules planted at nine months post-spill. Seedlings planted at six months after the spill survived, but growth was more rapid for seedlings planted at later dates. Despite these and other successes in reforestation, it is important to remember that the reestablishment of a fully functioning mangrove ecosystem requires the parallel recovery of all its natural component species (Vandermeulen and Gilfillan 1984), including the algae and animals of the prop root communities, the forest-floor inhabitants, and the arboreal species. Recovery to a fully functioning state may not be possible until PHCs are degraded into non-toxic compounds, as was indicated by an infaunal study (Gilfillan et al. 1981) that provided evidence of incomplete recovery of the forest-floor infauna at five years after the *Zoe Colocotroni* spill.

Coral Reefs

Until recently, subtidal corals were thought to be invulnerable to oiling, based on a review of oil spill incidents up to 1975 (Johannes 1975). Loya and Rinkevich (1980) and Vandermeulen and Gilfillan (1984) cited later studies that strongly refuted Johannes' (1975) assertion that "there appears to be no evidence that oil floating above reef corals damages them." The earlier field studies on which Johannes based his conclusion were largely anecdotal in nature in that they did not include investigations into any of the possible sublethal effects or long-term lethal effects of oil on corals.

Recent investigations concerning the effects of oil spills on coral reefs (summarized in **Table 15.3**) have shown that oil can kill or damage corals through exposure routes that were not considered in earlier studies. Intertidal corals can be smothered by direct contact with oil (Johannes et al. 1972; Jackson et al. 1989), whereas corals located at greater depths may be affected by water-soluble components from oil slicks passing over coral reef communities (Vandermeulen and Gilfillan 1984). The formation of stable oil-in-water emulsions provides a third route of oil contact with deep subtidal corals in areas where reefs and reef crests are exposed to waves and strong currents (Bak and Elgershuizen 1976; Marshall and Batista in review). Entrained oil droplets (as described in Nadeau and Bergquist 1977) may be carried to coral polyps by currents or wave-created turbulence. Oil may also sink when particles of sediment or organic matter adhere to the oil (The International Tanker Owners Pollution Federation, Ltd. 1986; Guzman et al. in review). Heavy crude oils such as Venezuelan crudes, which have specific gravities near 1.0, require the addition of only very small amounts of suspended particulates to exceed the specific gravity of seawater (approximately 1.025). Mousse (water-in-oil emulsions) can also be sunk by similar small additions of particulate matter. The formation of a mousse displaces oil and replaces it with seawater, thereby increasing specific gravity. Adhesion of a sufficient amount of suspended sediment particles may then sink the mousse. Oil stranded on sandy shorelines may become mixed with beach sediments and, if this mixture is then washed off the beach, it may sink (as observed by Diaz-Piferrer 1962 at the *Argea Prima* spill site) and come into contact with subtidal coral communities. Bleedwater (water containing PHCs that leaches from oiled sediments) may be an additional pathway by which nearshore corals can be oiled. The long-term effects of bleedwaters (Mackin 1950), which may carry PHC fractions from oiled mangrove forest-floor sediments into nearshore marine environments, on corals and other tropical shallow-water biota are unknown.

Table 15.3. Effects of oil spills on coral reefs (Adapted from: Loya and Rinkevich 1980).

Spill	Amount Spilled	Reported Effects	Reference
World War II, Japtan Island (Enewetak)	Unknown	Many porous rocks and boulders near the remains of the ship still heavily tarred in 1974	Johannes (1975)
World War II, several tankers, Gulf of Mexico and Caribbean Sea	Unknown	No effects reported	Dennis (1959), U.S. Coast Guard (1959, 1969)
World War II, Dry Tortugas	Unknown	Young mangroves of 4 to 5 yr were killed	Odum and Johannes (1975)
1962, ARGEA PRIMA, Puerto Rico	10.68 million liters	Mortalities of adult and juvenile lobsters, crabs, sea urchins, sea stars, sea cucumbers, molluscs, and fish; *Thalassia* beds degenerated; rocky areas denuded of algae; extensive damage to mangrove-swamp habitat	Diaz-Piferrer (1962)
1964, BROTHER GEORGE, Dry Tortugas	0.5 million liters	Possible mortalities of *Acropora palmata*	Jaap et al. (1989)
1966, BRITISH CROWN, Persian Gulf	27.70 million liters Qatar crude	No effects reported	Beynon (1971), Nelson-Smith (1973)
1967, R. C. STANER, Wake Island, Pacific Ocean	23.49 million liters gasoline, jet fuel, turbine fuel, diesel, Bunker C	About 2,500 kg of reef fish killed and stranded; large mortalities of molluscs and sea urchins	Gooding (1971)
1968, GENERAL COLOCOTRONIS Installation, Eleuthera, Bahamas	5.34 million liters	No effects reported	Spooner and Spooner (1968)
1968, OCEAN EAGLE, San Juan, Puerto Rico	Unknown	Many mortalities among intertidal organisms due to oil and emulsifier, including fish, molluscs, and algae; recovery good	Cerame-Vivas (1968)
1968, WITWATER, Galeta Island, Canal Zone	3.18 million liters diesel oil, Bunker C	Harmful effects to meiofauna, mangroves, and fiddler crabs; elimination of algae; reef corals least affected	Rutzler and Sterrer (1970)
1970, ENNERDALE, Seychelles	21.36 million liters fuel	No effects reported	Nelson-Smith (1973)
1970 pipeline break, Tarut Bay, Saudi Arabia	15.90 million liters Arabian light crude	Mortalities among crabs, molluscs, fish; mangrove trees less affected	Spooner (1970)

Table 15.3. (Continued).

Spill	Amount Spilled	Reported Effects	Reference
1970, OCEANIC GRANDEUR, Torres Strait, North Great Barrier Reef	1.22 million liters crude	No detrimental effects on corals and associated fauna; good subsequent recovery	Smithsonian Institution (1971a)
1970, unknown tanker near Pennekamp Coral Reef State Park, Florida Keys	Unknown; slick 121 km long, 0.80 km wide	No apparent effects; no apparent stranding of oil	Smithsonian Institution (1971b)
1971 M/V SOLAR TRADER, West Fayu, Caroline Islands	0.55 million liters fuel and lubricating oils	Numerous dead lobsters and clams; survey 8 mo afterward reported large algal growth on corals in the area	Smithsonian Institution (1973)
1974, SYGMA, Stockton Bight, east coast of Australia	0.43 million liters heavy fuel	13 km of beaches affected; no reported damage to marine life	Hughes (1974)
1975, M/V LINDERBANK, Fanning Atoll, Pacific Ocean	9.82 million liters copra palm oil, coconut oil, cocoa beans	Mortalities of fish, crustacea, and molluscs; afterward extensive growth of *Enteromorpha* and *Ulva*; reportedly complete recovery of original coralline algal community after 11 mo	Russell and Carlson (1978)
1975, GARBIS, Straits of Florida	0.24 to 0.48 million liters crude	No coral damage reported	Chan (1976, 1977)
1969-1979, two oil terminals, Eilat, Red Sea, Israel	Many small-scale oil spills, various tankers (crude oil)	Decrease in coral and fish diversity; lack of colonization by hermatypic corals in reef areas chronically polluted by oil; damage to reproductive system of corals	Fishelson (1973, 1977), Loya (1975, 1976), Rinkevich and Loya (1977, 1979), Loya and Rinkevich (1979)
1986 Bahia las Minas Refineria Nacional, Panama tank failure	8.0 million liters, 70% Venezuelan and 30% Mexican crude	Mortalities of subtidal reef corals seen as decrease in coral cover; substantial sublethal effects; *Siderastrea siderea* suffered most with new partial mortality occurring 1 yr after the spill; long-term study underway	Cubit et al. (1987), Jackson et al. (1989), Burns and Knap (1989), Guzman et et al. (in review)

Reef corals readily take up hydrocarbons from seawater (e.g., Burns and Knap 1989) but, when placed in hydrocarbon-free seawater, they are slow to depurate. Certain coral species (e.g., *Siderastrea siderea* in **Photograph 15.2**) have proven to be highly sensitive to absorption of oils' toxic compounds, to ingestion of oil droplets from oil-in-water emulsions, or to smothering by oil (in intertidal locations).

Long-term sublethal effects (e.g., changes in fecundity in adult corals) and lethal effects (e.g., death of established colonies and/or reduced survival of newly recruited corals) may result from chronic exposures to low concentrations of oil (Bak 1987). In Aruba, long-term exposure of reef corals to refinery effluents has resulted in various "subtle" effects, such as reduced coral cover, deteriorating spatial structure, lowered rates of recruitment or lowered survivorship of new recruits, and the complete absence of certain coral species (*Acropora palmata* and *Montastraea annularis)*. These effects were noticeable as differences between reefs upstream to and downstream from the path of a current of constant direction that carried refinery effluents across several reefs. Similar observations have been made repeatedly on the chronically oiled coral reefs at Eilat, Israel in the Red Sea (**Table 15.3**). Other observations of short- to long-term effects of oil on corals involve tissue damages (i.e, gonad damage and muscle atrophy) and/or changes in many basic physiological processes (e.g., decreases in calcification rates, decreased production of zooxanthellae, and increased mucus production). Other effects are summarized in **Table 15.4**. Oil spill damage assessments of coral reefs (and other habitats) typically end when oil is no longer obviously present; the sublethal effects of long-term, chronic exposures to PHCs (i.e., bleedwaters as a potential source of PHCs) have been completely missed in all such short-term studies of oil spill effects on coral reefs.

The Bahia las Minas study now underway in Panama (Cubit et al. 1987; Jackson et al. 1989; Guzman et al. in review) is the first study of sufficient scope and duration to document long-term effects of a large, crude oil spill on Caribbean and Atlantic coral reef communities. Concentrations of PHCs in seawater, coral tissues, and in nearby habitats (coral reef, seagrass meadow, and mangrove forest sediments) are being monitored by personnel from the Bermuda Biological Station for Research (Burns and Knap 1989). Hydrocarbon concentrations in coral tissue reached levels ranging from 1.3 ± 0.3 μg/mg lipids at a moderately oiled site to 25.5 ± 6.0 μg/mg lipids at a heavily oiled site.

Table 15.4. Stress responses shown by corals exposed to oil and oil fractions (From: Fucik et al. 1984).

Change in calcification rate	Impaired sediment clearance ability
Coenosarc tissue damage	Impaired polyp retraction
Decreased zooxanthellae production	Increased mucus production
Expulsion of zooxanthellae ("bleaching")	Larval death
Gonad damage	Muscle atrophy
Impaired feeding	Premature extrusion of planulae
Impaired larval settlement	Tissue death

Coral coverage on subtidal reefs, as well as the species composition, was determined by intensive surveys which were completed just before the Bahia las Minas spill occurred. In the initial post-spill coral reef surveys (Jackson et al. 1989), it was obvious that major changes had occurred in the total area of living coral tissue on heavily oiled reefs. Coral cover in shallow ($\leq$3 m) water, at a very heavily oiled site at Punta Galeta, decreased by 96 to 51% from the pre-spill to the first post-spill survey. Similar decreases in coral coverage were also seen in other areas. Sublethal effects were readily noticed; these included bleaching and swelling of tissues, heavy production of mucus, and partial mortality seen as recently dead areas devoid of coral tissue on coral colonies (**Photograph 15.2**). Globules of oil were often seen on coral surfaces. Some of the recently dead areas were surrounded by dark halos which are characteristic of bacterial infections. The frequency and the sizes of recently dead tissue patches on the most common massive corals increased markedly with the amount of oiling at each reef and decreased with water depth (Figure 8 in Jackson et al. 1989).

Changes in coral coverage and in species abundances, in Bahia las Minas and at unoiled control sites, have been monitored at yearly intervals since August 1986. Recruitment, reproduction, growth rate (by schlerochronological techniques), and partial mortality studies are also underway. It is hoped that these data will be interpretable based on observations of PHC concentrations in coral tissues and in the surrounding reef and non-reef habitats. A major concern in this, and the other studies underway in Panama, is that natural variation between sites and the effects of other societal pressures (i.e, siltation due to coastal deforestation, sewage pollution, other small oil spills, etc.) will obscure more subtle oil effects (Jackson et al. 1989; Guzman et al. in review; Marshall and Batista in prep.).

Seagrass Beds

Seagrass communities are vulnerable in intertidal and very shallow subtidal locations (**Photograph 15.3**). Deeper seagrass flats may completely escape oil exposure, if weather conditions, sea states, and suspended sediment loads do not produce conditions which emulsify oil in seawater and/or cause oil and emulsions to sink. The highly diverse infaunal and epibiotic assemblages are both vulnerable and sensitive to water soluble, emulsified, and sedimented components of PHCs.

The damages done by oil spills to the biota of seagrass meadows have usually been dismissed as insignificant. It had been assumed until recently, based on inadequate evidence, that floating oil slicks would pass over subtidal seagrass beds without effect. Chan (1976) reported that oil clingage, pumped out of the *Garbis* in the vicinity of the Marquesas Keys, floated over seagrass flats during high tides, between Boca Chica Key and Little Pine Key, without noticeable effects on *Thalassia* or *Halodule*. Empty (but still articulated) shells of *Pinctada radiata*, a pearl oyster which is common in Florida Keys' seagrass beds, accumulated on beaches soon after the *Garbis* incident. Chan (1976) attributed the mass mortality of these organisms to the oil spill. No other observations were made in subtidal seagrass beds.

Oil from the *Zoe Colocotroni* spill in Puerto Rico caused *Thalassia testudinum* leaves to blacken and eventually to be shed. Plant rhizomes apparently were not killed, because new seagrass growth was seen in the oiled areas within 10 months of the spill. Various large invertebrates were killed (**Table 15.5**) and quickly washed up on shore. Infauna were not measurably affected. The 1962 spill from the *Argea Prima* resulted in *Thalassia* meadow "degeneration." Diaz-Piferrer (1964) described neither the magnitude of the damage nor the depth ranges of the degenerating seagrass beds.

Table 15.5. Effects of oil spills on seagrass bed communities.

Spill	Amount Spilled	Reported Effects	Reference
1968, WITWATER, Bahia las Minas Panama	3.18 million liters diesel and Bunker C	No effects reported	Rutzler and Sterrer (1970), Birkeland et al. (1976)
1972, ARGEA PRIMA, Puerto Rico	10.68 million liters crude	*Thalassia* beds degenerated	Diaz-Piferrer (1964)
1973, ZOE COLOCOTRONI, Cabo Rojo, Southern Puerto Rico	5.34 million liters Venezuelan crude	Some *Thalassia* died; later some areas had rejuvenated growth from formerly exposed mat of rhizomes; urchins, sea cucumbers, prawns, conchs killed; infauna not measurably affected.	Nadeau and Bergquist (1977)
1975, GARBIS, Lower Florida Keys	0.24 to 0.48 million liters barrels crude clingage and water emulsion	*Thalassia* not damaged; *Pinctada radiata* (pearl oysters) killed in large number	Chan (1976, 1977)
1978, AMOCO CADIZ, Roscoff, France	236 million liters light Middle East crude	*Zostera marina* shed leaves after they blackened but did not die; Amphipoda reduced in diversity and numbers; Tanaidacea, Cumacea, and Echinodermata reduced in numbers	den Hartog and Jacobs (1980), Jacobs (1980)
1986, Refineria Nacional, Bahia las Minas, Panama	8.0 million liters of 70% Venezuelan and 30% Mexican crude	Intertidal *Thalassia* bed was killed and washed away, exposing bare rock; subtidal *Thalassia* leaves blackened, seagrass did not die; study of effects on infauna and epifauna underway	Cubit et al. (1987), Jackson et al. (1989), Marshall and Batista (in prep.)

The only other reports of oil damages to seagrass communities are those from *Zostera marina* beds in France oiled by the *Amoco Cadiz* (den Hartog and Jacobs 1980; Jacobs 1980) and from *Thalassia* meadows oiled by a refinery tank failure in Panama (Jackson et al. 1989; Marshall and Batista in review). In each case, the investigators monitored changes in plant biomass and intensively sampled the grassbed-resident infaunal and epifaunal assemblages. The most noticeable differences between pre-spill and post-spill (France) and control and oiled (Panama) seagrass beds were large decreases in abundances (France) and the virtual absence (in oiled Panamanian seagrass beds) of several orders of small crustaceans and all classes of echinoderms. Oiled intertidal seagrass beds were destroyed in Panama, but not in France. In Panama, after the dead intertidal seagrass beds decayed, sediments washed away and exposed a bare-rock platform. Seagrass leaves, in the oiled subtidal seagrass beds of both France and Panama, blackened and were shed. No seagrass mortality was noticed in France, but the landward-most edges of heavily oiled, subtidal seagrass meadows in Panama have been receding continuously since the spill (M. Marshall, pers. observ.).

In Panama, macroinfaunal groups that seemed to be adversely affected by oiling included bivalves, brachyurans, ophiuroids, polychaetes, sipunculids, and burrowing shrimp. As noted in Jackson et al. (1989), this is the first time that such an effect has been suggested for certain macroinfaunal groups in seagrass meadows. Epifaunal groups negatively affected by oil included amphipods, certain species of caridean shrimp, sea urchins, sea cucumbers, starfish, and grassbed-resident fishes (including parrotfish, gobies, and blennies). Because these observations were based on comparisons between oiled sites and unoiled control sites, it was necessary to follow them up by post-spill surveys in order to determine if the oiled sites would "recover" (defined as becoming more like the unoiled control sites). The post-spill surveys were made at quarterly intervals through April 1989.

It is obvious from the above summaries and from **Table 15.5** that oil can have a large negative effect on *Thalassia* meadow communities. This is especially true for intertidal and shallow, subtidal seagrass beds. As mentioned for corals, seagrass beds in areas adjacent to reef crests or other areas where waves break may be exposed to oil-in-water emulsions entrained by the action of breaking waves. Most tanker spills occur during bad weather (Bak and Elgershuizen 1976) when sea states would be most likely to act on oil slicks to produce such emulsions. Suspended sediment and organic matter concentrations also may be highly elevated during stormy weather or during the South Florida rainy season. Because one of the widely touted and most important ecological roles of seagrass meadows is that they trap fine particles of sediment (Zieman 1982), they may also act as traps of sinking droplets of oil combined with sediment particles (as is described by The International Tanker Owners Pollution Federation, Ltd. 1986).

Compared with other shallow, coastal communities, seagrasses are not highly susceptible to damage from oil spills, except in their upper ranges of distribution. Where oil has contacted seagrasses that are just intertidal or just subtidal, damage has been extensive, while plants in deeper subtidal beds are generally unharmed by direct effects of the oil (Chan 1977; Cubit et al. 1987; Jackson et al. 1989). These instances point out how vulnerable much of South Florida's seagrass meadows would be to an oil spill. As noted by Zieman in **Chapter 4**, the priceless nursery meadows of Florida Bay in Everglades National Park and much of the western portions of the Lower Keys are extremely vulnerable to oiling because so much of this area consists of shallow mud-banks that are emergent on very low tides. The standing crop of seagrass leaves on these mudbanks in western Florida Bay is about twice as high as the average standing crop of the bay as a whole (**Chapter 4**).

It may be that in many instances the effects of seagrass bed oiling have been overlooked. The monitoring of effects of oil spills on seagrass beds (and all other habitats) requires that all components of the community associated with the seagrasses be monitored. It is possible to envision meadows of lush growths of *Thalassia* without the highly diverse assemblages of small animals that are normally associated with *Thalassia*. In Florida Bay, many of these small animals are juveniles of commercially important species--e.g., spotted seatrout *Cynoscion nebulosus* and gray snapper *Lutjanus griseus* (Rutherford et al. 1989a,b,c); red drum *Sciaenops ocellatus* (Tilmant et al. 1989); spiny lobster *Panulirus argus* (Davis and Dodrill 1989); and stone crab *Menippe mercenaria* (Lindberg and Marshall 1984). The other, non-commercially important species are of equally high "commercial" value because they are the animals which trophically link the commercially important species to the high primary productivity of seagrass meadows (i.e., Carr and Adams 1973; Leber 1983; Marshall 1985; Harrigan et al. 1989; Hettler 1989).

Rocky Intertidal Areas

The biota of rocky intertidal zones and intertidal reef flats are vulnerable to oiling due to their location within the tidal range. Unlike mangrove forests, coral reefs, and seagrass meadows, the major structural component of rocky intertidal communities is not alive. The rocks to which sessile biota attach, either directly or indirectly through other species, may, however, be thickly coated with oil (**Photograph 15.4**) and become unsuitable for settlement. Obviously, the living organisms on rock surfaces may also be coated by and smothered in baked-on layers of tar-like, weathered oil. Some of the organisms, e.g., barnacles and certain bivalves, which live in the intertidal, can shut themselves off from the oil through adaptations to normal tidal exposures of varying length, and thus may not die immediately. They may not be able to resume normal functioning until oil is cleaned from their shell surfaces, and this may not happen soon enough to prevent massive mortalities.

Recovery of the communities typical of rocky shores would depend highly on the degree of exposure of the oiled shore. Heavy and weathered oils would readily adhere to rough surfaces, while light oils would be less sticky (Getter et al. 1981). Following the Bahia las Minas spill in Panama, the seaward edges of rocky reef flats were rapidly cleaned of baked-on tarry oil by high surf and strong turbulence (Jackson et al. 1989; Cubit and Burgett in press). Oil remained visible for longer periods of time at points located at increasing distances from the seaward edge of the reef flat.

Little attention has been given to the effects of oiling on the epibiota of rocky intertidal areas in the tropics. The *Argea Prima* spill in Puerto Rico killed the normal assemblage of algal species found in the rocky intertidal (Diaz-Piferrer 1962). The mixed-species algal community which was destroyed was replaced by a number of blue-green algal species which had not been abundant before the spill. Chan (1976) reported that oil from the *Garbis* caused temporary (several month) decreases in the abundances of crabs and gastropods. Animals living on the seaward side of the rocky platforms' highest point did not appear to be affected by oiling. Chan witnessed a die-off of echinoderms at three weeks post-spill in landward areas of the platform where they were known to be abundant on the day the oil landed on the rocky platform. Echinoderms on the seaward face of the platform were not obviously affected. A bloom of blue-green algae was noted on the *Garbis* oil-affected areas of the rocky intertidal platform.

In Panama, after the Bahia las Minas oil spill, the percentages of coverage by several species of algae, sessile animals, and other epifauna declined on a rocky intertidal reef flat (Cubit et al. 1987; Jackson et al. 1989). A bloom of microalgae soon

after the spill actually reduced the percentage of bare rock surface. Species abundances of algae, animals, and bare rock, on this same reef flat had been monitored for up to 15 years prior to the spill. It was thus easy to conclude that major decreases had occurred in the percentage of the reef flat covered by these organisms. Several of the algal species returned to greater than pre-spill abundances within 12 to 18 months of the spill. Of the animals, only the colonial anemone *Zoanthus* had returned to typical abundance after 18 months. The site of this reef flat at Punta Galeta is exposed to the washing and cleansing effects of extremely heavy surf during the Panamanian dry season (December through April). Although oil was baked onto exposed surfaces during the extremely low tides that occurred during the oil spill, the oil was rapidly washed away. Dispersants were not used and were not needed to remove the baked-on oil.

Sandy Intertidal Areas

The vulnerability to oiling of exposed beaches and their inhabitants is high (reviewed by Ganning et al. 1984). Stranding of weathered oil in accumulations of seagrass wrack on sandy beaches on Boca Chica Key was one of the most obvious signs of the *Garbis* oil spill. Chan (1977) found that oil leaching from the debris permeated the sandy substrate to a depth of 10 cm.

Amphipods and crabs normally associated with the wrack were not found immediately after the *Garbis* spill, but recolonization of fresh wrack occurred within six months as clean wrack washed into the areas. The sensitivity to oil exposure of macroinfaunal species typical of this habitat varies from taxon to taxon (Chan 1976, 1977). If oil is washed away soon after a spill, then recovery of the macroinfaunal community may be very rapid. If oil is buried in anoxic layers beneath surface sediments, it may persist for years, and the infauna will not recover rapidly. *Ixtoc I* oil had little effect on Texas beaches because it was highly weathered before it reached Texas and because the oil (3,900 metric tons of an estimated 476,000 metric tons spilled) that did reach the beach, between August and September 1979, was quickly washed away by a tropical storm on 13 September 1979 (Gundlach et al. 1981).

In Puerto Rico, following the *Argea Prima* spill, oil mixed with beach sand and the mixture was then washed away, resulting in heavy erosion in some areas (Diaz-Piferrer 1962). The beaches of Bahia Sucia were heavily oiled, and were the site of intense cleanup operations following the *Zoe Colocotroni* spill of Venezuelan crude (Nadeau and Bergquist 1977). These authors did not study the effects of oiling on the beach fauna because the cleanup crews and equipment obstructed much of the beach.

IMPLICATIONS FOR SOUTH FLORIDA

Potential Sources of Oil Spills

Accidents that have resulted in major oil spills in the past can be divided into five categories, as listed in **Table 15.6**. Tankers (and other vessels carrying fuel oils) are currently the only potential source of major spills in the study area. Offshore drilling and production would introduce some additional risk of spillage; potential sources include blowouts, loading accidents, or accidents during transportation of oil to refineries (**Chapter 12**). The Minerals Management Service (MMS) has stated that oil produced in the study area probably would be offloaded directly to tankers from production platforms. Pipelines to a common loading point might be used if the size of the find justified the expense. For economic and legal reasons, it is unlikely that pipelines to shore or onshore storage tanks would be constructed in the area (**Chapter 12**).

Table 15.6. Existing and potential sources of oil spills in South Florida.

Source	Present or Future Threat	Oil Type(s)
Tanker accident	Present/future	Crude, diesel
Pipeline break	Future	Crude
Loading spills	Future	Crude at offshore terminal diesel in fueling rigs, vessels
Offshore well blowouts	Future	Crude
Storage tank failures	Future	Crude/refined products

Tanker accidents involving crude oil and freighter accidents involving fuel oils are the most likely source of large spills (defined as those $\geq$160,000 L, or 1,000 barrels[2]) in the area, whether or not offshore production occurs (**Chapter 12**). The existing risk of a large oil spill from tanker traffic is probably much greater than the risk of a spill from offshore operations, unless huge new oil reserves are discovered. However, if oil production does occur in the area, the risk of a large spill would increase (**Chapter 12**). Transfer and transportation operations would be the most likely source of a large spill if offshore drilling and production were to occur in the study area; blowouts are unlikely in South Florida for geologic reasons (State of Florida and MMS 1989b).

Transport of Spilled Oil

South Florida's marine habitats are vulnerable to oiling from offshore accidents because of the flow patterns of the major currents that run close to shore throughout the area.

The major deepwater current in the eastern Gulf of Mexico is the Loop Current. This current enters the Gulf of Mexico through the Straits of Yucatan, flows northward into the east-central Gulf of Mexico, then turns clockwise and exits through the Straits of Florida, where it is referred to as the Florida Current (see **Chapter 2**). Drift bottle releases (Williams et al. 1977) and recent trajectory modeling (State of Florida and MMS 1989b) show that the Loop Current and Florida Current could rapidly transport oil spilled on the Southwest Florida shelf (north of the Dry Tortugas) around to the Lower Keys, Reef Tract, and Southeast Florida coast.

Oil carried by the Loop Current and Florida Current could impinge upon coastal areas through eddy or meander formation, or through winds blowing across the axis of the main current. As an example, oil spilled from the *Garbis* on 18 July 1975 in the Straits of Florida, at a point 42 km (23 nmi) south-southwest of the Marquesas Keys, oiled shorelines from Boca Chica Key to Little Pine Key beginning on 21 July 1975 (Chan 1976). Easterly winds blowing across the main axis of the Florida Current drove the slick ashore and spread it across a 56-km (30-nmi) stretch of shoreline.

Trajectory modeling reported by the State of Florida and MMS (1989b) shows that oil spilled north of the Dry Tortugas could become entrained in the Loop Current, carried around to the Straits of Florida, then blown back through the Florida Keys to hit Florida Bay or the Southwest Florida coast. In some of the cases simulated, an oil spill could have reached these areas faster by the indirect route than by direct transport toward the mainland coast.

[2]Barrels are the customary unit used by the MMS to report spill volumes (1 barrel = 42 U.S. gallons, or about 160 L).

Oil entrained in the Loop Current could also be transported out of the study area without hitting the coast. For example, a 1970 spill from an unknown vessel completely missed the Florida Keys, despite the formation of a 120 km (65 nmi) long slick seen at John Pennekamp Coral Reef State Park (Smithsonian Institution 1971b).

The Loop Current and the Florida Current provide a powerful mechanism for exposing much of the study area to spilled oil. At the same time, an oil slick entrained in these major currents would be subject to shear because of the large velocity gradient; consequently, a slick could become elongated and broken into many long streamers, and mousse formation could be enhanced (State of Florida and MMS 1989b).

The eastern shoreline of the Florida Keys from Miami to Key West is partially protected from large waves by the Florida Reef Tract. The Reef Tract and inshore flats between it and the shoreline are relatively narrow (4.0 to 9.6 km [2.2 to 5.2 nmi]). An extensive coral reef forms an irregular ridge along the seaward edge (**Chapter 4**). At numerous locations, such as Fowey Rocks, Alligator Reef, American Shoals, Western Sambo Reef, etc., reef crests are within a few meters of the sea surface. These shallow reef tops partially shelter the inshore flats from high waves, but they would also enhance the turbulent conditions, in any sea states beyond light to moderate chops, which can promote the formation of oil-in-water emulsions. The shallow flats behind the reef crests are characterized by patch reefs, isolated coral heads, and vast expanses of seagrass meadows. Natural shorelines inside of the reef flat are bordered by extensive areas of intertidal rock, mangrove forests, and sandy beaches. The nearshore environment of the Ten Thousand Islands and the Everglades National Park, the shallow mudbanks of Florida Bay, and the western shoreline of the Florida Keys are characterized by seagrass meadows, mud/sand flats, patch reefs, and mangrove forests. All of the biota that produce living structure in these habitats can be killed by oil.

Sensitive Shorelines and Shallow-Water Habitats

Coastal habitats in the study area are best discussed in geomorphologic units: Cape Romano through the Ten Thousand Islands, including the Big Cypress watershed; Everglades National Park and Florida Bay; and the Florida Keys and Reef Tract.

Cape Romano through the Ten Thousand Islands

South of Cape Romano, one of the most complex and oil-sensitive shorelines in the entire State of Florida begins (Getter et al. 1983). The Ten Thousand Islands area includes thousands of small mangrove-fringed and/or mangrove-covered islands. The area is the terminus of the Big Cypress Swamp, a large freshwater marsh system (**Figure 15.4**). Water from the Big Cypress Swamp flows into the Ten Thousand Islands area through a series of rivers and bays (e.g., Pumpkin Bay and Pumpkin River; Fakahatchee Bay and Fakahatchee and East Rivers; and Chokoloskee Bay and Ferguson, Brown, and Turner Rivers). Thousands of mangrove islands, interspersed within hundreds of shallow bays and channels, extend from the larger coastal bays toward the open sea for 6.5 to 8 km (3.5 to 4.3 nmi). Many of the estuarine bays contain large areas of seagrass meadows and/or macroalgal-dominated benthic communities (Odum et al. 1982; Drew and Schomer 1984). The fringing mangroves are mostly the red mangrove and, as such, have well-developed prop root communities. The shallow, mangrove-lined bays of this area serve as nursery grounds for juveniles of numerous species of estuarine-dependent fishes that are spawned offshore. The seaward-most islands have coarse-grained sandy beach faces. Several navigable canals exist among the islands and from the coast to the sea--e.g., Coon Key Pass, Tripod Key Channel, Faka Union Canal, Fakahatchee Pass, West Pass, Indian Key Pass, Sandfly Pass, Chokoloskee Pass, and Rabbit Key Pass. The nearshore area from Cape Romano southward contains extensive seagrass beds.

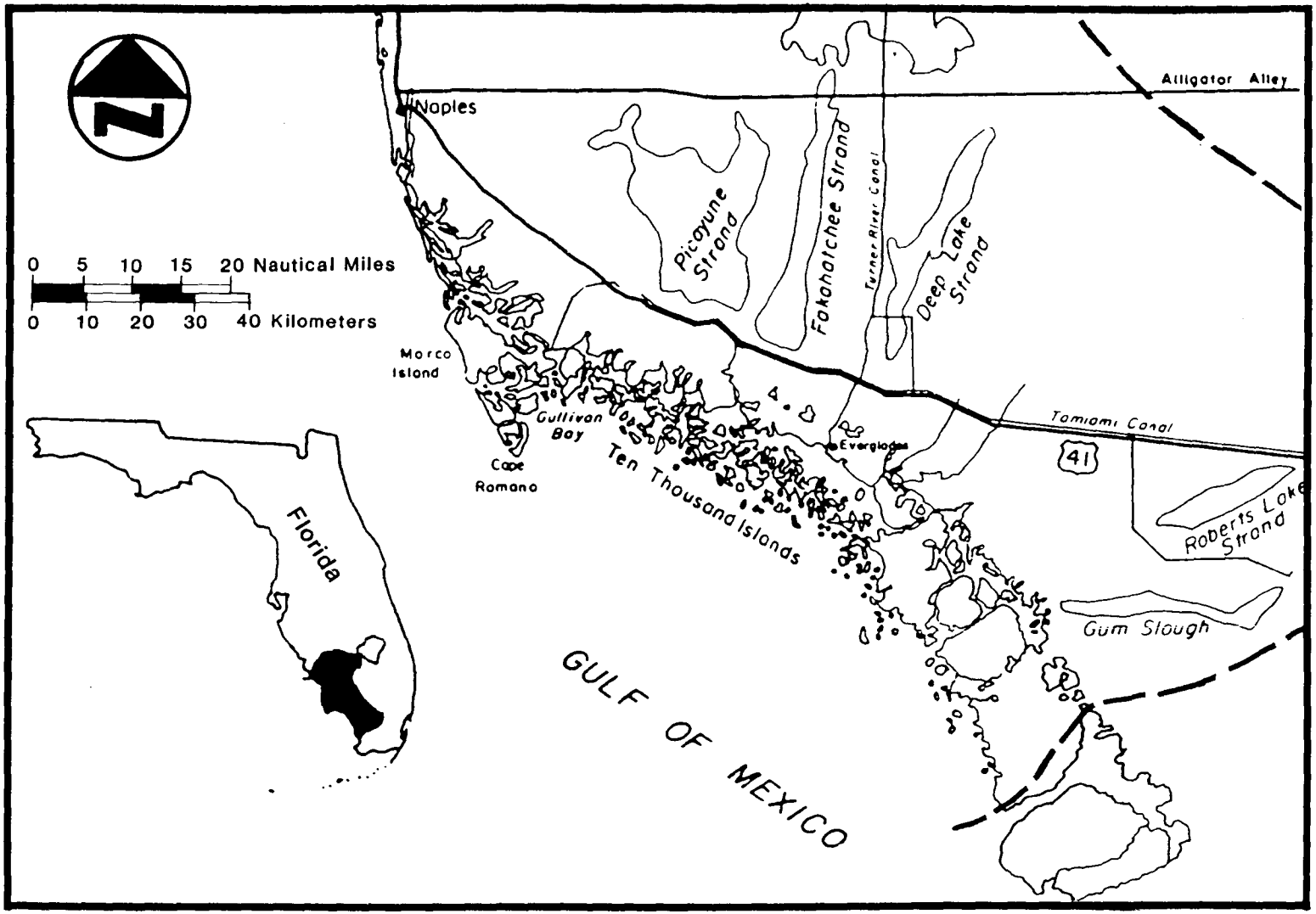


Figure 15.4. The Ten Thousand Islands area of the Southwest Florida coast (From: Drew and Schomer 1984). The complex network of islands and channels in this area would make oil spill response difficult or impossible.

The geographical complexity of this area would make it impossible to control a spill once it reached the Ten Thousand Islands because the only protective measure that would be feasible, aerial spraying of dispersants, would add to (instead of protect against) the damaging effects of oiling (Ballou et al. 1987). Other methods of oil spill control and cleanup will not work on this coastline; it is too shallow for skimmer boats, too complex for booms, and the forest is an impenetrable barrier to all machinery and most people.

The Ten Thousand Islands area serves as critical habitat for several protected species (the American crocodile, sea turtles, numerous birds, and the Florida manatee). It is a rookery ground for many other bird species, and migratory birds congregate along this coast in the winter months (see **Chapter 9**); it is also a nursery ground for commercially important fishes and invertebrates. Odum et al. (1982) provided an extensive listing of some of the many animals and plants which inhabit these extremely productive mangrove forests. Ecologically, there is no other area like it on this continent. It is currently stressed by encroaching development and by human-caused changes in the water flow patterns through the Big Cypress watershed (Drew and Schomer 1984). A massive oil spill reaching here would very likely alter or permanently destroy its beauty, which is dependent on a myriad of intricate interactions between plants and animals. Estimates of recovery times for mangrove forests damaged by oil spills range from 25 to 80 years (Cairns and Buikema 1984).

The tremendous amount of damage to mangroves in Panama after the Bahia las Minas spill would seem insignificant in comparison to the damage that could be done to the Ten Thousand Islands of Florida by a spill of the same size. Teas et al. (1989) reported that an estimated total of 75 ha of mangroves were destroyed in Panama. The steep increase in land elevation between the sea and dry land in Panama limits mangroves to small fringing, basin, riverine, and overwash forests. If oil penetrated deeply into the much larger forests characteristic of the Southwest Florida coast, the areal extent of damage would possibly be several orders of magnitude above that done to Panamanian mangrove forests. Snedaker (**Chapter 4**) described the inundation patterns of the five mangrove forest types found in South Florida. From these descriptions, it is obvious that they are not all equally vulnerable to oiling, because not all forest types are inundated by daily high tides. Basin forests, for example, are inundated primarily during the wet season. Despite their varying chances of being oiled, tidal conditions can be such that all of the forest types are oiled by one large oil spill in the right area at the right time.

Everglades National Park and Florida Bay

Pavilion Key, just south of the Ten Thousand Islands, marks the northern limit of Everglades National Park. The shoreline of the park can be divided into four areas: the bay area from Ten Thousand Islands to Lostmans River; the riverine area including Lostmans River, Broad River, Harney River, and Shark River; the Cape Sable/Whitewater Bay area; and the Taylor Slough/Florida Bay area. This region and its ecological complexity are described in more detail than is possible here by Schomer and Drew (1982) and by Odum et al. (1982).

The coastal area between the Ten Thousand Islands and Lostmans River is predominantly composed of mangrove-lined bays and islands fronting pine/palmetto upland. Some small creeks (e.g., Charley Creek) penetrate the upland to the inland freshwater marshes.

The riverine area, which extends to the south from Lostmans River, consists of coastal swamps and lagoons which connect the Shark River Slough and the estuarine embayments of the Lostmans River/Broad River drainage to the Gulf of Mexico. These areas are highly productive estuarine systems containing complex plant and animal

communities. Mangrove-lined rivers and channels, mangrove forests which grow in vast wetland expanses, salt marshes in more upland areas, and "backbays" characterize the coastal swamp and lagoonal area (Odum et al. 1982). Oil in these areas would do much damage to shellfish populations (as described in Palik and Lewis 1983), mangrove root communities, mangrove forests, and shallow beds of aquatic vegetation.

Oyster, Ponce de Leon, and Whitewater Bays are the largest lagoons of the coastal swamp and lagoon system; they are located at the southern end of the Shark River slough. Cape Sable, an upland area, separates much of Whitewater Bay from the Gulf of Mexico, but oil slicks could enter Whitewater Bay by the numerous channels and smaller bays which link it to the Gulf of Mexico at its northwestern tip. There are many hectares of mangroves along the shores of these connecting channels and bays and on the islands within the bay. The inhabitants of these mangroves would be similar to those found in the Ten Thousand Islands region. If oil did enter Whitewater Bay and the other bays in this area, then much of the oil-sensitive mangrove forest and its inhabitants would be vulnerable to the various effects of oil exposure.

Cape Sable consists predominantly of coarse sand beaches, beach ridges, and salt ponds gradating into tropical hardwood hammocks, salt prairies, salt marshes, and the mangroves of Whitewater Bay. Salt ponds on Cape Sable (the largest of which is Lake Ingraham) contain extensive tidal flats. The most conspicuous oil-sensitive faunal component of Cape Sable are loggerhead sea turtles, which may be highly sensitive to oil during nesting activities.

The Taylor Slough portions of the Everglades and Florida Bay are geologically and biologically a contiguous unit. The shoreline bights and offshore mangrove islands, shoals, and banks surrounding deeper "lake" areas were formed during the sea level rise and fall during the Pleistocene glacial period. These shallow lakes and banks (maximum depth approximately 2.4 m) contain extensive benthic algal and seagrass beds (Zieman 1982). Several canals connect inland marshes to Florida Bay westward from and adjacent to Flamingo. East of Flamingo, the connection of freshwater marshes to Florida Bay is less distinct in the shoreline bays and bights.

Thalassia testudinum, *Syringodium filiforme*, and *Halodule wrightii* are the major species of seagrasses found on mudbanks and in the shallow "lakes" of Florida Bay (**Chapter 4** and Zieman 1982). These same three seagrass species are also found in Panamanian shallow-water seagrass meadows (M. Marshall, pers. observ.). Many of the mudbanks, which divide Florida Bay into several subenvironments (Schomer and Drew 1982), are either intertidal or just subtidal. Oil drifting onto these shallow banks at high tide could damage or kill seagrasses, algae, infauna, and epifauna. If conditions were such that the oil had been mixed with sediment particles or otherwise entrained into the water column, it might also affect the deeper seagrass beds and corals typical of much of this area. Because there is little tidal flushing in certain parts of Florida Bay, oil that entered these areas might remain trapped there for very long periods. Complete degradation of the oil and/or tropical storms passing through the area might be the only two means by which oil could be removed.

Much of the highly diverse biota of Florida Bay has been recently described by papers presented at a symposium on Florida Bay (Bull. Mar. Sci. 44). The papers presented at this symposium (e.g., Bowman et al. 1989; Enos 1989; Holmquist et al. 1989; Mazzotti 1989; Rutherford et al. 1989a,b,c; Sogard et al. 1989; Tabb and Roessler 1989; Wilson 1989) included descriptions of important Florida Bay habitats and of many of Florida Bay's plants and animals.

The Florida Keys and Reef Tract

The Florida Keys extend south from the Florida peninsula, beginning at a point east of Biscayne Bay. Soldier Key, the Ragged Keys, Sands Key, Elliott Key, and Old Rhodes Key are the major islands north of Key Largo. These relatively uninhabited islands (Biscayne National Park is located on Elliott Key) have exposed rocky platforms on the seaward shore, and mangroves on the bay side separated by cuts (e.g., Sands Cut, Caesars Creek, Broad Creek), allowing for tidal exchange of bay water and the waters of the Atlantic Ocean.

As noted in **Chapter 2**, the Florida Keys can be divided geologically into the Upper and Lower Keys. The Upper Keys are oriented along the axis of the island chain, whereas the Lower Keys (from Big Pine Key to Key West) are oriented perpendicular to the chain and are separated by channels connecting Florida Bay to the Atlantic Ocean (**Figure 15.5**). In the Upper Keys, the largest island, Key Largo, is loosely connected to the Florida peninsula by a series of mangrove-lined bays containing extensive seagrass beds. In the Lower Keys, seaward edges of the islands vary from coarse-grained sand beaches (e.g., Bahia Honda State Park and Grassy Key) to rocky intertidal platforms. The Content Keys, Mud Keys, and Lower Harbor Keys extend westward and are surrounded by large expanses of sheltered mangrove lagoonal systems, tidal flats, and seagrass beds. Cuts and channels between the islands of the Lower Keys are small and numerous. It would be very difficult to protect the shoreline and nearshore habitats of this area from floating oil during any weather conditions; during severe weather, it might be impossible.

Mangrove islands and shallow-water seagrass beds extend westward from Key West to the Marquesas Keys. The islands of the Marquesas are fringed by mangroves and are surrounded by many hectares of very shallow seagrass meadows. Coral reefs are located at the seaward edges of the seagrass meadows. The Dry Tortugas lie west of the Marquesas Keys across the Southeast Channel. These islands are sand shoals within the lagoon of an atoll-like reef system. The Dry Tortugas are also a foraging and nesting ground for many oceanic and coastal birds; Sooty Terns nest in huge numbers on Bush Key (**Chapter 9**). Extensive seagrass beds are located in the shallow waters of the lagoon (Davis 1982). It would be very difficult to protect the mangroves, reefs, seagrass meadows, and their associated animal assemblages from large oil slicks. Bad weather would make it impossible.

The Florida Reef Tract begins approximately 4.0 to 9.6 km (2.2 to 5.2 nmi) offshore from Soldier Key at Fowey Rocks and roughly parallels the Keys at that distance from shore (**Figure 15.5**). The extent of the Reef Tract, its structure, and its component species are described by Jaap (1984) and Jaap and Hallock (**Chapter 4**).

The isolated coral colonies of reef flat areas, patch reefs (in Florida Bay and Hawk Channel), and major bank reefs typical of the Florida Reef Tract, could, under the proper set of conditions, be vulnerable to the effects of oil wherever a large slick landed. A large spill could affect a large part of the Florida Reef Tract or miss it completely. Of three spills that have occurred in this area since 1964, two spills beached (the *Brother George* spill in 1964 at the Dry Tortugas, and the *Garbis* spill in 1975, in the Straits of Florida), while a third spill from an unknown source missed the Florida Keys (unknown vessel, 1970, slick sighted near the John Pennekamp Coral Reef State Park). The Pennekamp spill missed the Keys despite the formation of a 120 km (65 nmi) long slick. The 1975 *Garbis* spill (0.24 to 0.48 million liters, or 1,500 to 3,000 barrels) oiled a 56-km (30-nmi) stretch of the Lower Keys. The *Brother George* spill (0.5 million liters, or 3,100 barrels) killed birds and may have killed some coral (Jaap et al. 1989) around the Tortugas, but did not affect other areas further to the east of the

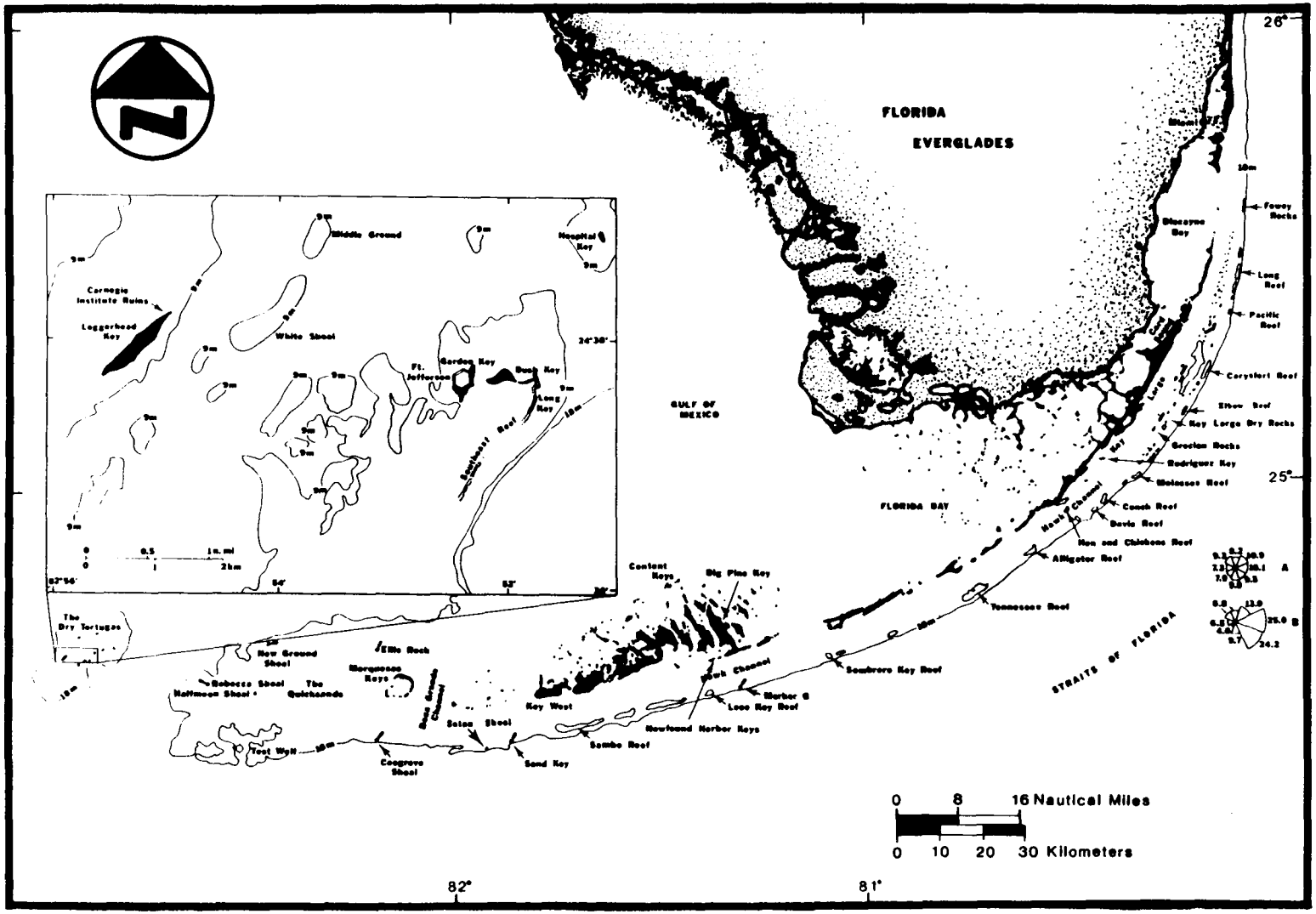


Figure 15.5. The Florida Keys, Reef Tract, and Dry Tortugas (From: Shinn et al. 1989).

spill site. Oil spill trajectory analyses for the Southwest Florida area (see **Chapter 12**) have not explicitly modeled spreading of oil (R. LaBelle, MMS, pers. comm. 1990 to N. Phillips). It is thus not possible to predict the total area that might be oiled as a result of a particular size of spill.

If a large spill did occur, and the conditions were right, it could alter the structure of much of the reef for a very long time. Reefs do not recover rapidly; an estimate of 10 to >50 years (Cairns and Buikema 1984) seems conservative, because many of the large coral colonies on any reef exceed 100 years of age (e.g., Hudson et al. 1989; Guzman et al. in review). If recovery of the reef is defined as a return to pre-spill structural complexity, then it would take 100+ years for the oldest coral heads to regrow and achieve the same level of structural complexity. The effects of oil on the other flora and fauna of the Florida Reef Tract can only be guessed.

Protected Species

Reptiles, birds, fish, and marine mammals associated with South Florida's coastal and marine habitats are variously vulnerable to oiling and sensitive to oil. Included in these groups are several protected species (**Table 15.7**).

Reptiles

The American alligator (*Alligator mississippiensis*) is found in a variety of habitats, including salt marshes, canals, ditches, and mangroves of low-salinity waters in South Florida (Mazzotti 1989). In Florida, alligators are no longer in danger of extinction, but the U.S. Fish and Wildlife Service (USFWS) classifies them as Threatened due to similarity in appearance to Louisiana alligator populations, which are Endangered.

The American crocodile (*Crocodylus acutus*) in South Florida is Endangered, representing the only population in the U.S. Approximately two-thirds of the reproducing U.S. population resides in Everglades National Park (Mazzotti 1989). Mangroves are considered to be critical habitat for the American crocodile (Odum et al. 1982). Crocodiles are distributed along the mudflat- and mangrove-fringed shorelines of Whitewater Bay, Florida Bay, Key Largo, Big Pine Key, and southern Biscayne Bay. Primary nesting sites are on sandy shoreline beaches and on marl banks of coastal creeks. A single nesting site is used for several years. Eggs are laid in late April or May and hatch in late July or early August (Mazzotti 1989). Nesting success of crocodiles is dependent on a variety of factors including erosion, flooding, and predation (Mazzotti 1989). Oil spills in the Panama Canal area are reportedly responsible for "long-term damage to the resident crocodile populations" (Getter et al. 1984), but the effects of oil on crocodile eggs, juveniles, and adults is otherwise unknown. No evidence for this quoted statement was offered by these authors.

According to the State of Florida and MMS (1989a), the likelihood of an oil spill reaching critical nesting habitats of the American crocodile is remote. However, because of the Endangered status and restricted range of the species, any contamination of nesting sites (as described by Mazzotti 1989) would be very serious.

Five species of sea turtles occur in the study area: the green sea turtle (*Chelonia mydas*), the hawksbill sea turtle (*Eretmochelys imbricata*), the Kemp's ridley sea turtle (*Lepidochelys kempi*), the leatherback sea turtle (*Dermochelys coriacea*), and the loggerhead sea turtle (*Caretta caretta*) (**Chapter 8**). Of these, the green (Florida nesting population), hawksbill, Kemp's ridley, and leatherback sea turtles are Endangered, whereas the loggerhead sea turtle is Threatened.

Table 15.7. Protected species in the South Florida study area that are vulnerable to oiling. Status as of 1 July 1989 from Florida Game and Fresh Water Fish Commission (1989). Occurrence in the study area based on **Chapter 8** (for marine mammals and sea turtles), **Chapter 9** (for birds), and Table VI-3 in State of Florida and Minerals Management Service (1989a) (for others).

Species	Status*		Populations Particularly Vulnerable to Oiling of Coastal Habitats
	Federal	State	
REPTILES			
American alligator (*Alligator mississippiensis*)	T(s/a)†	SSC	
American crocodile (*Crocodylus acutus*)	E	E	
Green sea turtle (*Chelonia mydas*)	E	E	
Hawksbill sea turtle (*Eretmochelys imbricata*)	E	E	
Kemp's ridley sea turtle (*Lepidochelys kempi*)	E	E	
Leatherback sea turtle (*Dermochelys coriacea*)	E	E	
Loggerhead sea turtle (*Caretta caretta*)	T	T	x
BIRDS§			
American Oystercatcher (*Haematopus palliatus*)	–	SSC	
Arctic Peregrine Falcon (*Falco peregrinus tundrius*)	T	E	x
Bald Eagle (*Haliaeetus leucocephalus*)	E	T	
Brown Noddy (*Anous stolidus*)	–	–	x
Brown Pelican (*Pelecanus occidentalis*)	–	SSC	
Great Blue Heron (*Ardea herodias*)	–	–	x
Least Tern (*Sterna antillarum antillarum*)	–	T	
Little Blue Heron (*Egretta caerulea*)	–	SSC	
Mangrove Clapper Rail (*Rallus longirostris insularum*)	UR2	–	
Osprey (*Pandion haliaetus*)	–	SSC¶	
Piping Plover (*Charadrius melodus*)	T	T	
Reddish Egret (*Egretta rufescens*)	UR2	SSC	x
Roseate Spoonbill (*Ajaia ajaja*)	–	SSC	x
Roseate Tern (*Sterna dougallii*)	T	T	x
Snowy Egret (*Egretta thula*)	–	SSC	
Sooty Tern (*Sterna fuscata*)	–	–	x
Southeastern Snowy Plover (*Charadrius alexandrinus tenuirostris*)	UR2	T	x
Tricolored Heron (*Egretta tricolor*)	–	SSC	
FISH			
Key blenny (*Starksia starcki*)	–	SSC	x
Key silverside (*Menidia conchorum*)	–	T	x
MAMMALS			
Blue whale (*Balaenoptera musculus*)	E	E	
Fin whale (*Balaenoptera physalus*)	E	E	
Humpback whale (*Megaptera novaeangliae*)	E	E	
Right whale (*Eubalaena glacialis*)	E	E	
Sei whale (*Balaenoptera borealis*)	E	E	
Sperm whale (*Physeter macrocephalus*)	E	E	
Florida manatee (*Trichechus manatus latirostris*)	E	E	x
Key deer (*Odocoileus virginianus clavium*)	E	E	

* E = Endangered; T = Threatened; SSC = Species of Special Concern; UR2 = under review, but substantial evidence of biological vulnerability and/or threat is lacking; UR5 = still formally under review, but recent information indicates species is more widespread or abundant than previously believed.

† Florida populations are no longer in danger of extinction, but are classified as Threatened due to similarity in appearance to Louisiana populations, which are Endangered.

§ Ten protected bird species listed in Table 9.1 are not included here because of the small chance of exposure to oil. These are the American Swallow-tailed Kite (*Elanoides forficatus*), Burrowing Owl (*Athene cunicularia*), Cape Sable Seaside Sparrow (*Ammodramus maritimus mirabilis*), Florida Sandhill Crane (*Grus canadensis pratensis*), Limpkin (*Aramus guarauna*), Merlin (*Falco columbarius*), Northern Harrier (*Circus cyaneus*), Southeastern American Kestrel (*Falco sparverius paulus*), Swainson's Hawk (*Buteo swainsoni*), and White-crowned Pigeon (*Columba leucocephala*). The Great Blue Heron is not a protected species, but is listed because of distinct subpopulations of the two color morphs adapted to subtropical conditions, with the range of the white morph restricted to the study area. The Sooty Tern and the Brown Noddy are also not protected species, but they are listed because the Dry Tortugas are the only important breeding site in the continental U.S.

¶ Applicable in Monroe County only.

Of the five sea turtle species, only the loggerhead nests in the study area, along the Southwest Florida coast, at Cape Sable, and in the Lower Keys, the Marquesas Keys, and the Dry Tortugas (**Chapter 8**). The sandy beaches of South Florida are important nesting grounds for these sea turtles (Davis and Whiting 1977). On the mainland, the nesting season extends from April through September; in the Florida Keys, the season is from April through June.

Loggerhead turtle eggs in the nest and young hatchlings could be adversely affected by exposures to spilled oil. An oil spill reaching turtle nesting areas could contaminate eggs and result in developmental anomalies and mortality (Fritts and McGehee 1981). Weathered crude oils are less damaging than are fresh crudes. Cleanup activities could destroy nests or compact sand over them, which would prevent hatchlings from digging out of the nests. Turtle nests have been successfully relocated from oiled beaches.

It is believed, as evidenced by beached, oiled carcasses, that oil from the *Ixtoc I* blowout killed adult green and Kemp's ridley turtles in the western Gulf of Mexico (Hall 1980). The magnitude of these oil-caused mortalities is unknown. Juvenile green and loggerhead turtles have been killed by active ingestion of tar globules (Witham 1978). Many other concerns over the effects of oiling on embryonic, juvenile, and adult sea turtles were expressed by participants in two conferences sponsored by the MMS and USFWS (Keller and Adams 1983; MMS 1989).

Post-hatchling sea turtles of several species are often found in offshore convergence zones consisting of *Sargassum* and debris. This is important because floating pollutants such as oil can become concentrated in the same convergence zones (Carr 1986).

Birds

Coastal and marine birds are the animals most likely to be severely affected if an oil spill were to come ashore in the study area. Sandy beach, mangrove, and marsh habitats are vital to many species of resident and migratory birds. Several of these species are Endangered, Threatened, or Species of Special Concern (**Table 15.7**). Surface and diving birds and other pelagic seabirds are frequently oiled and suffer great losses in offshore spills. As spills come ashore and into marsh areas, the wading birds and shorebirds are apt to become oiled. Gulls sometimes appear to be able to avoid serious mortality from oil (Alexander 1983). Upon oiling, bird feathers can become matted together. This causes loss of insulation, decreases buoyancy, and adds weight, which causes swimming and floating seabirds to sink deeper into the water and to lose body heat. Attempts to clean oiled birds have been marginally successful. Oiled birds may ingest oil during attempts to clean themselves, and they may ingest oil-contaminated food. Oil could cause pneumonia, irritation of the digestive tract, and adrenal cortical hyperplasia. Ingested oil could also reduce egg production. Oil applied to the egg-shell surface (i.e., transferred from the feathers of the incubating hen) has been shown to greatly reduce hatching success, and even a trace of oil on a fertilized egg can poison the embryo inside (Satchell and Carpenter 1989). Aromatic hydrocarbons are the most toxic; weathered oil, the least toxic (Alexander 1983).

Populations of several species of birds in the study area are especially vulnerable to oiling (see **Chapter 9** and **Appendix B** for further information). Many birds forage or nest in coastal habitats that could be oiled, and many are dependent on the continued health of the mangrove communities. Of particular concern are the following species:

- Arctic Peregrine Falcon (*Falco peregrinus tundrius*). This Florida Endangered subspecies is highly migratory. Nearly 300 individuals, representative of the subspecies' entire population, pause during spring and fall at Loggerhead Key in the Dry Tortugas, a critical area for these migrants (see **Chapter 9**). These falcons knock or force prey into the water and could thus become oiled during foraging.

- Great Blue Heron (*Ardea herodias*). Although not a protected species, both the blue and white color morphs within the study area appear to have a unique gene pool, the birds being notably adapted to subtropical conditions (see **Chapter 9**). Furthermore, the white morph's major range and nesting area restrict it to Florida Bay and the Lower Keys.

- Reddish Egret (*Egretta rufescens*). The Florida Bay population of this Florida Species of Special Concern is probably a unique one in terms of its gene pool, and the population is estimated at below 300 pairs. The Reddish Egret is a sedentary species that has become ecologically restricted to an area where the productivity of its food sources has become marginal.

- Roseate Spoonbill (*Ajaia ajaja*). The Roseate Spoonbill is a Florida Species of Special Concern. The species recovered from near extinction earlier in the century, but the population is once again stressed and in decline because of inadequate food supplies due to altered freshwater flow from the Everglades. The spoonbills in Florida Bay constitute a distinct subpopulation that has developed "traditions" (e.g., when and where to migrate and nest) to this area. This means that if the subpopulation were destroyed, the area would not be colonized by new individuals from other areas.

- Roseate Tern (*Sterna dougallii*). The South Florida population of this Threatened species is the only one in the U.S. south of North Carolina. A colony of about 300 breeding pairs on a freshly bulldozed Key West harbor island could be the largest colony in the eastern U.S.; the entire North American population is estimated at 2,500 pairs.

- Sooty Tern (*Sterna fuscata*) and Brown Noddy (*Anous stolidus*). Both species, though not classified as Endangered or Threatened, would be particularly vulnerable to oiling during their spring-summer nesting period at Bush Key in the Dry Tortugas. The Dry Tortugas are the only important nesting ground in the continental U.S. for both species. Sooty Terns nest on the ground just inland from the beach, and adults forage extensively in nearby waters, from March through August, with over 80,000 individuals present. Several hundred to several thousand Brown Noddies nest there from March through October. An oil spill (*Brother George*) contaminated the Dry Tortugas in January 1964 and killed numerous birds; fortunately, the spill occurred well before the Sooty Terns and Brown Noddies began to land (Robertson 1964), and most oil was removed before then.

- Southeastern Snowy Plover (*Charadrius alexandrinus tenuirostris*). Gulf coast beaches in the Cape Romano area are one of the few remaining nesting sites of this Florida Threatened species. It is estimated that only 100 to 200 animals remain in Florida (Kale and Maehr 1990).

Fish

Two protected fish species are found only in the lower Florida Keys: the Key silverside (*Menidia conchorum*) and the Key blenny (*Starksia starcki*). The Key silverside, a Florida Threatened species, inhabits the area between Big Pine Key and Key West, living in shallow, open bays having loose coralline sediments and shorelines bordered with mats of organic debris (State of Florida and MMS 1989a). The Key blenny, a Florida Species of Special Concern, is known only from Looe Key, where it occurs in channels between corals in water depths of $\leq$5 m (State of Florida and MMS 1989a). Both species are year-round residents. Because these species live only in shallow, coastal waters of the Lower Keys, a large oil spill could affect the entire known population of either species.

Mammals

Twenty-nine species of whales and dolphins are known or suspected to occur in the study area, including six Endangered species: the right whale (*Eubalaena glacialis*), the blue whale (*Balaenoptera musculus*), the fin whale (*B. physalus*), the sei whale (*B. borealis*), the humpback whale (*Megaptera novaeangliae*), and the sperm whale (*Physeter macrocephalus*) (**Chapter 8**). Little is known of the actual occurrence of these species in the study area, as most of the data are from strandings.

The most common cetacean in the study area is the bottlenose dolphin (*Tursiops truncatus*). Bottlenose dolphins are not Endangered or Threatened, but they are protected under the Marine Mammal Protection Act. Dolphins tend to concentrate in coastal areas and therefore, are more susceptible to contamination by spilled oil than are whales, which occur offshore. Bottlenose dolphins can detect and are inclined to avoid oil (Geraci and St. Aubin 1982; Geraci 1988). A dolphin or whale in the center of a fresh oil slick could inhale enough vapor or ingest enough oil to pose an immediate threat to its health. Possible sublethal effects to these animals include eye irritations (possibly resulting in blindness) and respiratory stress. In addition, cetaceans could be affected indirectly through consumption of contaminated food. However, as noted by Geraci (1989), none of these effects have been detected, or at least recorded with certainty, in connection with actual oil spills.

Of greatest concern among the marine mammals is the Endangered Florida manatee (*Trichechus manatus latirostris*). The species ranges throughout Florida and is the most common Endangered marine mammal in the study area (**Chapter 8**). Centers of manatee abundance include Southeast Florida from St. Lucie Inlet to Biscayne Bay and Southwest Florida from Charlotte Harbor through the Ten Thousand Islands (Irvine and Campbell 1978; Layne 1978; USFWS 1980; Irvine et al. 1981). During warmer months, manatees reside in rivers, shallow estuaries, and saltwater bays. In winter, they concentrate in heated effluent from power plants and in freshwater springs.

Neither the size nor the trend of the manatee population is known, but the minimum winter count in 1986 was 1,200 individuals (**Chapter 8**). The populations on the Atlantic and Gulf of Mexico coasts are believed to be isolated. Irvine et al. (1981) conducted a series of aerial surveys from July to December 1979 to examine the distribution and relative abundance of manatees from Bayport, Hernando County, south to the ranger station at Flamingo (Everglades National Park), Monroe County. A total of 297 groups of manatees, totaling 554 individuals, were observed during these surveys. Manatees were consistently observed in Whitewater Bay, Chevalier Bay, and in the Lopez River, but the largest concentrations were found in Collier County from Marco Island to Chokoloskee (an area which includes most of the Ten Thousand Islands). In 1989, the Florida Department of Natural Resources (FDNR) estimated that about 400

manatees occurred south of Fort Myers in Southwest Florida (B. Ackerman, unpubl. FDNR memorandum cited in State of Florida and MMS 1989a).

Based on observations at the *Peck Slip* oil spill (Puerto Rico), manatees may avoid oil slicks by retreating into unoiled tidal creeks and other uncontaminated areas (Getter et al. 1981). If contaminated by surface oil, manatees could be expected to suffer respiratory stress from inhaling fumes and oil, and to suffer damages to eye tissues from oil contact. They might eat contaminated aquatic vegetation, but no information is available on the effects of this route of hydrocarbon uptake (Fritts et al. 1983; St. Aubin and Lounsbury 1988). A spill during the winter months probably would pose the greatest threat to the population because the animals tend to congregate.

The Key deer (*Odocoileus virginianus clavium*) is an Endangered species found only on islands in the vicinity of the National Key Deer Refuge in Big Pine Key in the Florida Keys (Odum et al. 1982). Key deer prefer pine and hardwood forests but are found in red mangrove wetlands during the day. The total population is estimated at only 300 to 400 individuals and ranges over several hundred hectares. Key deer travel between islands by swimming. Potential effects from spilled oil are contamination of food sources and oiling of individuals traveling between islands. The effects of an oil spill on these animals have not yet been observed. It is possible that oiled deer would be subject to severe heat loss as a result of hair matting, and oil ingested through preening attempts might produce toxic effects.

Summary

Many protected species are found in the study area. All of those listed in **Table 15.7** are vulnerable to oiling; that is, individuals could be exposed to oil as a result of normal behavioral patterns and life habits. They may also be affected by loss of critical foraging and nesting habitats. Mortality to *individuals* of any protected species should be of great concern. In addition, *populations* of several species are particularly vulnerable to oiling. These include the loggerhead sea turtle, which nests in the study area; the Arctic Peregrine Falcon, which has nearly its entire population pause twice yearly at the Dry Tortugas; the Great Blue Heron, which has subpopulations adapted to the subtropics, with the white morph restricted to Florida Bay and the Lower Keys; the Reddish Egret and Roseate Spoonbill, both of which have small, restricted populations in Florida Bay; the Sooty Tern and Brown Noddy, whose nesting grounds at the Dry Tortugas are the only significant breeding ground in the continental U.S.; the Southeastern Snowy Plover, which nests on the beaches of the Cape Romano area; the Key silverside and Key blenny, two fishes found only in coastal waters of the Lower Keys; and the Florida manatee.

CONCLUSIONS

Two central conclusions are evident from this review:

- Much of the study area consists of habitats that are vulnerable and sensitive to oiling. Studies of previous oil spills have shown that mangrove forests, coral reefs, and seagrass bed communities can be severely damaged, depending on the degree of exposure to oil. Associated fauna, including endangered sea turtles, birds, fish, manatees, Key deer, and numerous invertebrates, could be killed, injured, or stressed.

- Characteristics of the shoreline and shallow coastal areas, particularly in Florida Bay, the Ten Thousand Islands, and the Lower Keys, would make it difficult or impossible to prevent oil spills from reaching highly vulnerable and sensitive coastal ecosystems. Once contaminated, areas such as mangrove forests and seagrass beds on shallow mudbanks would be difficult or impossible to clean.

Thus, the potential exists for serious damage from oil spills in the study area. However, it is difficult to predict how much damage would result from a large oil spill and how long that damage would remain apparent at the various levels of ecological structure. Information is lacking in three critical areas: (1) the extent of oiling cannot be predicted; (2) the adequacy of existing contingency plans to respond to oil spills is unknown; and (3) the time for damaged ecosystems to recover is unknown.

In 1975, a small spill from the tanker *Garbis* in the Straits of Florida 42 km (23 nmi) south-southwest of the Marquesas Keys oiled shorelines from Boca Chica Key to Little Pine Key (Chan 1976). Easterly winds blowing across the main axis of the Florida Current drove the slick ashore and spread it across a 56-km (30-nmi) stretch of sensitive shoreline. This information cannot simply be extrapolated to predict the extent of damage from larger spills. None of the trajectory modeling conducted to date has explicitly addressed the problem of spreading (see **Chapter 12**). Therefore, it is difficult to predict the extent of damage that would be realized in the event of a larger spill in the study area.

Because of the ecological, economic, and aesthetic value of South Florida's coastal and nearshore habitats, prevention of exposure to oil is critical. The mishandling of the recent *Exxon Valdez* spill in Alaska (National Response Team 1989) has called into question the adequacy of existing contingency plans nationwide. According to the Petroleum Industry Response Organization (PIRO), no existing oil spill response cooperative is equipped to handle spills larger than 4 million liters (25,000 barrels) in the open ocean, or 6.4 million liters (40,000 barrels) in coastal waters (PIRO Steering Committee 1990). The petroleum industry is working to develop the capability to respond to spills as large as 34.3 million liters (216,000 barrels), but this capability will not be in place for several years (PIRO Steering Committee 1990).

The adequacy of oil spill response measures is a critical issue. Trajectory modeling has shown that an oil spill on the Southwest Florida shelf north of the study area could reach Florida Bay, the Lower Florida Keys, the Florida Reef Tract, or the Dry Tortugas within 24 to 72 hours depending on spill location and prevailing winds and currents (State of Florida and MMS 1989b). Although the modeling results cannot simply be extrapolated to the study area, it is obvious that spills at some locations within the study area could reach these shorelines and resources within a few hours depending on environmental conditions. Depending on the meteorological conditions at the time of a spill, it would be difficult or impossible to prevent oil from reaching these sensitive shorelines and resources.

The question of how long the damage from an oil spill might remain apparent cannot even be approached with the data that are currently available. Recovery times cited earlier in this chapter are equivocal at best. No evidence is currently available for recovery rates after worst-case oil spills. Some oil spill effects may be transitory, e.g., the effects of oil on sandy beaches; but in South Florida, most sandy beaches are part of or close to habitat types of much greater complexity where damage could remain apparent for a long time.

Although much remains to be learned about natural variation in population fluctuations from year to year in South Florida marine areas, it is evident, based on oil spills which have occurred in other similar environments, that many of the species could be killed, injured, or stressed after exposure to oil slicks. Additional research into post-spill recovery rates, for each of the critical habitats, is needed. Most oil spill followup studies have been short-term descriptions of the damage that is obvious immediately after a spill. Even the five-year followup study of the Bahia las Minas refinery spill will be inadequate to determine habitat recovery rates for mangrove forests, mangrove prop-root communities, and coral reefs.

An adequate and agreed-upon definition of recovery is a necessity before such research should be undertaken. Ganning et al. (1984) discussed three definitions of recovery that are useful to different groups of those concerned about oil spill effects. The loosest definition is that recovery can be claimed when the environment is returned to usefulness as perceived and defined by the general public. Because much of the general public in South Florida is aware of the basic ecological fundamentals regarding marine habitat functioning, this may be a useful definition. The second definition given by these authors considers recovery as a restoration to the original functional and structural conditions but allows a change in the set of species that was present before a disturbance in community structure. This definition presumes that the original structural and functional conditions could be re-attained even if species composition changed. This would be an almost useless definition of recovery in Southwest Florida's complex shallow-water marine communities, where most of the structure-providing species are sensitive and vulnerable to oiling. There are no analogues to these species. The most strict definition of recovery, and the most appropriate from an ecological viewpoint, is that the damaged ecosystem must be returned to its original functional and structural conditions with its original species present. Recovery by this third definition would probably never be observed after a major oil spill in South Florida. As an example, coral colonies live for centuries (Hudson et al. 1989; Guzman et al. in press), and if large colonies, which provide much of the structural complexity of a coral reef community, are killed then recovery of corals and their associated biota would not occur during the lifetimes of the scientists assigned to monitor recovery.

A combination of the statements of research needs by the NRC (1989) and the Governor's Office of Planning and Budgeting (1988) would be a good framework on which to base further research efforts. The former is a review of the adequacy of environmental information in MMS Environmental Impact Statements for leasing off Southwest Florida; the latter is a review of MMS-sponsored biological surveys of the Southwest Florida shelf (Danek and Lewbel 1986; Continental Shelf Associates, Inc. 1987; Environmental Science and Engineering et al. 1987). Both reviews suggest that large data gaps exist in the identification of critical coastal habitats and in adequate the description of baseline conditions. These gaps need to be filled in order to document damages that might result from future oil spills and to provide estimates of community recovery rates. The most important recommendation of both reports is that long-term information on the distribution and abundances of various species needs to be considered to provide insights on trends and variations in populations and processes. Some of the research presented at the Symposium on Florida Bay (Bull. Mar. Sci. 44(1), 1989), if continued over longer periods of time, would partially address these needs. Continuous monitoring of the most critical habitats for several years is needed to provide baseline data.

Some specific suggestions for research needs relating to mangrove forests, coral reefs, and seagrass beds are presented below.

Mangrove Forests

Basic research on mangroves in the study area is so limited and equivocal that it is difficult to draw firm conclusions or to use the available information as a basis for management decisions. Some specific information needs are highlighted below.

Susceptibility of Stress-Adapted Mangroves to Increased Stress

Most mangroves within the study area grow under less-than-optimum conditions and can be classified as stressed. The best examples are the dwarf and stunted mangroves that are common to southeastern Dade County and the Florida Keys. Presumably, the stresses consist of one or more of the following physical characteristics of those environments: inherently low site fertility, minimal or irregular exposure to freshwater runoff and its entrained load of terrigenous nutrients, absence of tidal inundation during the 4- to 6-month low-water season, and/or episodes of extreme hypersaline conditions. Although stressed, these mangroves perform all of the functions and processes associated with unstressed mangroves, notwithstanding their low population density, rates of primary productivity, and standing stock biomass.

A key ecological question concerning these stressed trees is whether or not in their stressed state they are resistant or susceptible to added stress. Specifically, one could argue that these mangroves have "adapted" to the ambient stresses, and that capability to cope with stress gives them a measure of resistance; in other words, they are more hardy than unstressed trees. Conversely, an equally strong argument could be made that these stressed mangroves exist close to the limits of survival, and that any additional drain of metabolic resources would lead either slowly or quickly to the eventual loss of the affected population.

In the context of oil spill assessments and experiments involving mangroves, all of the work appears to have focused on unstressed, or normal, mangroves. Furthermore, there is inadequate information in the extant literature that would allow speculation on the differential responses by normal and stressed mangroves to additive stresses.

Mechanism of Acute Mangrove Mortality in an Oil Spill

A consistent observation in the oil spill assessment literature involving mangroves is that following a relatively heavy oiling, there is rapid mortality of the affected mangroves. This is attributed to mechanical suffocation caused by the oil covering the gas exchange surfaces of the affected trees. Whereas this is at least superficially a logical conclusion, there are no experimental results which confirm it. Moreover, the one unpublished experiment involving gas (nitrogen) exchange in oiled pneumatophores (M. Brown, pers. comm. to S. Snedaker) indicates that the rate of gas exchange drops in proportion to the viscosity of the oil, but that it does not entirely cease. If gases can pass through oiled surfaces, this raises a number of questions about the actual mortality mechanism. First, there could be a threshold effect which involves the absolute rate of exchange. Second, the rates of oxygen uptake and carbon dioxide release could be differentially affected to the detriment of the plant. For example, inadequate oxygen could lead to respiratory collapse, or the internal buildup of carbon dioxide could lead to a deleterious change in intracellular pH.

A final, probably more important, question focuses on the total rhizosphere gas exchange, rather than the fractional portion which moves across plant tissue surfaces. In most oil spill assessments, researchers reported oiling of sediment surfaces in addition to the oiling of trunks, prop roots, and pneumatophores. If a significant fraction of the

total rhizosphere gas exchanges occurs across the sediment surface, then closure of this pathway alone could lead to respiratory problems irrespective of whether or not plant surfaces remain functional. With respect to post-spill cleanup policies, the potential for a successful cleanup might hinge on whether the effort is focused on the cleaning of plant surfaces or the restoration of rhizosphere gas exchange across the sediment surface.

Mechanism of Delayed Stress and Mangrove Mortality following an Oil Spill

There are several reports in the oil spill literature which suggest that delayed mortality occurs in mature mangroves, months to years following a spill incident. For example, fringing *Laguncularia racemosa* which were oiled during the *Howard Star* spill in Hillsborough Bay in October 1978, survived until a freeze in February 1980 when they defoliated (Getter et al. 1980a). Because the 1980 freeze affected only oiled *L. racemosa* in the area, it is presumed that those trees were chronically stressed by the oil residues.

In this regard, the persisting oil or its breakdown products appear to impose a sublethal, chronic stress that heavily taxes the metabolic resources of the trees. Thus, the affected mangroves are metabolically unable to cope with an additional stress irrespective of whether it is an isolated event (e.g., a freeze) or part of a normal, seasonal cycle in the physical environment. The underlying chronic stress could either be a direct response to an accumulation of toxic materials (e.g., aromatic petrogenic compounds) in the sediment, or an indirect response to a severely altered sediment chemistry. For example, entrained oil in the sediment could inhibit the anaerobic remineralization of organic matter, or otherwise alter the stoichiometric ratio or absolute availability of nutrients.

The evolving conventional wisdom on this topic suggests that mangrove damage following a spill event could be significantly minimized, and mangrove recovery enhanced, through artificial fertilization. Ostensibly, fertilization would help overcome any nutrient deficiency relative to mangrove growth, and help to stimulate the microbial breakdown of petrogenic compounds in the sediment. The extent to which these benefits could be achieved, and whether this approach is substantially better than current cleanup practices, are questions that warrant research.

Uptake of Petrogenic Compounds by Mangroves

The question of whether mangroves take up and accumulate petrogenic compounds, particularly in leaf tissues, is not satisfied by the equivocal results in the published and gray literature. It is known, however, that mangroves can take up and concentrate a variety of inorganic and organic compounds, frequently without observable effects on the plant. The consequence of this phenomenon is that biologically concentrated noxious or potentially toxic materials could enter nearshore food webs via detrital pathways. The fate and effects of the type of transfer are neither known nor amenable to speculation. This same problem also applies to the question of the fate and effects of the sediment release of petrogenic 'bleedwater' into the nearshore environment.

Fertilization and Mangrove Recovery

Mangrove growth and development are highly dependent on nutrient availability (among other factors, such as freshwater availability). The existence of large areas of dwarf or shrub mangroves in Southeast Florida is presumed to be the result of insufficient nutrient availability, coupled with both infrequent tidal inundation and reduced freshwater exposure. The observed high growth and survival response of mangroves to artificial fertilization at planting sites around South Florida indicates that fertilization could be used to accelerate recovery of mangroves following an oil spill. In this regard, it is hypothesized that the growth stimulation would not be the result of any effect of a fertilizer on oil *per se*, but rather the result of providing the affected trees with the metabolic ability to overcome the stress of oiling. This is a critical topic, insofar as the testing of other recovery-enhancement approaches (e.g., use of dispersants) has not been attempted (nor is it likely to be) in the carbonate environment of South Florida.

Coral Reefs

Little is known of the damage and recovery potential of any reef system. Coral reef ecosystems are complex, and we currently lack adequate information on reef structure and functions to accurately predict the effects of oil spilled over or near the Florida Reef Tract. The Bahia las Minas oil spill study in Panama (Jackson et al. 1989) will continue to provide a wealth of information on oil effects on reefs, but the structure and function of the Panamanian reefs is considerably different from that of the reefs along the Florida Keys. Species composition is similar, but the structure of the reefs and their proximity to mangrove shorelines is different. There are reefs in Florida that are similar in structure to the Panamanian reefs; they are close to mangrove-lined shorelines and are adjacent to shallow seagrass meadows. It is recommended that a study be conducted to determine the exact applicability of the entire Panama project to South Florida. This recommendation is based on the numerous citations that this ongoing project has received in this review, in scientific journals and documents, and in the popular press.

Long-term baseline data on South Florida coral reefs are needed if we are to be able to separate oil spill effects from changes due to other natural and anthropogenic stresses. **Chapter 4** documented the stresses that affect Florida Reef Tract corals, and Jackson et al. (1989) briefly discussed the effects of development on the oiled Panamanian reefs. The signs of other stress can be separated out from oil effects by the proper experimental design if adequate baseline data are available (Green 1979). The approach used by Jackson et al. (1989) fully considers and addresses the possible complications of the other anthropogenic and natural changes to which the corals of the Caribbean coast of Panama have been subjected.

Most studies of oil spills and coral reefs have addressed damages to corals and neglected the effects of oil on other species associated with reefs. Many of these species play important roles in the dynamics of reef erosion and accretion. Subtle effects of oil spills may be manifested in changes in the balance of erosional and accretional processes. The studies currently underway in Panama do not address the effects of spilled oil and recovery of this component of the reef community. An important aspect of direct hydrocarbon effects, under the dynamics of reef topography, is the question of the rate at which Florida's reefs will have to accrete in order to keep up with predicted rising sea levels during the upcoming years. It is likely that most species would not be able to survive under "normal" conditions even without exposure to petroleum hydrocarbons. Spilled oil may slow coral growth and reef accretion, in localized areas, to levels at which no species could keep up with sea level changes.

The following additional topics for further research are suggested:

- Exact mapping of reefs along the Florida Reef Tract, and determinations of species composition and age-class distributions of corals on parallel transects along depth contours on major and minor reefs. Surveys should be updated on a regular schedule (e.g., 3- to 5-year intervals) or as soon as possible after major storms. The goal is to develop precise inventories and sensitivity maps of the coral communities in South Florida.

- Determinations of the proximity of reefs to mangrove shorelines and other habitats that might retain oil and act as a chronic source of hydrocarbons.

- Additional studies of the behavior of oil in calm, moderate, and rough seas with sediment loads typical of the Florida Reef Tract and Florida Bay.

Seagrass Beds

As noted by Zieman (**Chapter 4**), research on seagrasses has progressed to the point that it is usually possible to determine the *qualitative* effects of natural environmental and anthropogenic stresses. It is still vitally necessary to develop information to allow *quantitative* assessments as well.

Long-Term Studies

Seagrasses in South Florida have not been monitored for extended periods of time (**Chapter 4**). Thus, no information exists on long-term *natural* variation in undisturbed seagrass meadows. It is currently impossible to separate the effects of random but extreme climatic events from those caused by anthropogenic stresses and habitat modification.

The MMS-sponsored Panama oil spill study originally included plans for a five-year followup study of spill effects on seagrass meadow communities. The study was recently shortened to include collections up to three years post-spill (April 1989), despite the continued exposure of oiled seagrass beds to weathered oil releases from shoreline mangrove forests. Continued study of the Panamanian seagrass beds is necessary, considering the importance of seagrass environments to South Florida.

Succession and Community Development

As noted in **Chapter 4**, numerous data gaps exist concerning seagrass succession and community development. The broad pattern of succession has been described, but the conditions which lead to the transition of one species to another are not quantified. In addition, the relative roles of (1) vegetative reproduction (clonal growth), (2) seed and seedling success, and (3) rooting of free vegetative segments in maintaining and dispersing seagrass beds is unknown. If spreading and reproduction are largely clonal, the reduced genetic diversity could have important effects on the ability of a bed to tolerate various stresses. Studies of succession and community development are particularly relevant to predicting recovery of oiled seagrass beds.

Additional Research Directions

The research directions suggested above apply primarily to seagrasses. It is also vitally important to study the effects of oil on seagrass-associated flora and fauna, because seagrass beds in Florida Bay are critical to many economically important species. These studies should include both the economically important species, in all life cycle stages, and the complex assemblages of algae and animals on which they depend. Examples include the following:

- Studies of the weathering rates of crude oil (from the Sunniland Trend) and changes in toxicity through time of that oil buried in seagrass meadows.
- Descriptions of seagrass blade epifloral and epifaunal communities in Florida Bay, and determinations of the effects of oil on those communities.
- Determination of the effects of oil on larval, post-larval, juvenile, and adult stages of commercially and ecologically important species found in seagrass beds.

Models

For knowledge and predictability of seagrass systems to advance, it is necessary to develop conceptual and simulation models of the most important processes. Primary among these processes are the interaction of light, temperature, and salinity on seagrass growth, as well as models describing successional processes. These will allow scientists and managers to generalize rather than rely totally on innumerable site-specific studies (**Chapter 4**). These data could be incorporated into the seagrass production "bullet" shown in **Figure 15.1**. Similar production models should be produced for mangroves, mudflats, and algal bottoms. As is suggested by **Figure 15.1**, coral reef ecosystems may influenced by changes in shoreline and other shallow habitats. **Figure 15.2** suggests interactions between oil and pelagic, intertidal, and subtidal habitats. A combination of these two models with detailed information on oil effects and long-term natural processes, would be most useful to scientists and managers who are interested in predicting oil spill effects.

REFERENCES CITED

Alexander, M. M. 1983. Oil, fish and wildlife, and wetlands. *N.E. Environ. Sci.* 2(1):13-14.

Atwood, D. K., and R. L. Ferguson. 1982. An example study of the weathering of spilled petroleum in a tropical marine environment: *Ixtoc I. Bull. Mar. Sci.* 32:1-13.

Bak, R. P. M. 1987. Effects of chronic oil pollution on a Caribbean coral reef. *Mar. Pollut. Bull.* 18:534-539.

Bak, R. P. M., and J. H. B. W. Elgershuizen. 1976. Patterns of oil sediment rejection in corals. *Mar. Biol.* 37:105-113.

Baker, J. M. 1970. The effects of oils on plants. *Environ. Pollut.* 1:27-44.

Baker, J. M. 1981. The investigation of oil industry influences on tropical marine ecosystems. *Mar. Pollut. Bull.* 12:6-10.

Baker, J. M. 1982. Mangrove swamps and the oil industry. OPP 1:5-22.

Baker, J. M., I. M. Suryowinoto, P. Brooks, and S. Rowland. 1981. Tropical marine ecosystems and the oil industry; with a description of a post-oil spill survey in Indonesia mangroves. In *Petromar 80. Petroleum and the Marine Environment, Eurocean*, 679-703. London: Graham & Trotman Ltd.

Ballou, T. G., R. E. Dodge, S. C. Hess, A. H. Knap, and T. D. Sleeter. 1987. *Effects of a dispersed and undispersed crude oil on mangroves, seagrasses and corals.* API Publ. No. 4460. Washington, DC: American Petroleum Institute.

Beynon, L. R. 1971. Dealing with major oil spills at sea. In *Water pollution by oil*, ed. P. Hepple, 187-193. London: Institute of Petroleum.

Birkeland, C., A. A. Reimer, and J. R. Young. 1976. *Survey of marine communities in Panama and experiments with oil.* EPA-600/3-76-028. Narragansett: U.S. Environmental Protection Agency, Ecological Research Series.

Bowman, R., G. V. N. Powell, J. A. Hovis, N. C. Kline, and T. Wilmers. 1989. Variations in reproductive success between subpopulations of the osprey (*Pandion haliaetus*) in South Florida. *Bull. Mar. Sci.* 44:245-251.

Burns, K., and A. Knap. 1989. The Bahia las Minas oil spill: Hydrocarbon uptake by reef building corals. *Mar. Pollut. Bull.* 20:391-398.

Cairns, J., Jr., and A. L. Buikema, Jr. 1984. Workshop summary. In *Restoration of habitats impacted by oil spills*, ed. J. Cairns and A. L. Buikema.

Carr, A. 1986. *New perspectives on the pelagic stage of sea turtle development*. NOAA Tech. Mem. No. NMFS-SEFC-190. Panama City, FL.

Carr, W. E. S., and C. A. Adams. 1973. Food habits of juvenile marine fishes occupying seagrass beds in the estuarine zone near Crystal River, Florida. *Trans. Am. Fish. Soc.* 102:511-540.

Chan, E. I. 1976. Oil pollution and tropical littoral communities: Biological effects of the 1975 Florida Keys oil spill. M. S. thesis, Univ. of Miami.

Chan, E. I. 1977. Oil pollution and tropical littoral communities: Biological effects of the 1975 Florida Keys oil spill. In *Proceedings, 1977 Oil Spill Conference, 539-542*. API Publ. No. 4284. Washington, DC: American Petroleum Institute.

Cerame-Vivas, M. J. 1968. The wreck of the *Ocean Eagle*. *Sea Front.* 15:222-231.

Commonwealth of Puerto Rico and the Environmental Quality Board of the Commonwealth of Puerto Rico vs. the SS *Zoe Colocotroni*, her engines, appurtenances, etc., et al. 1973. Civil No. 252-73. United States District Court for the District of Puerto Rico.

Commonwealth of Puerto Rico vs. the SS *Zoe Colocotroni*. 1978. Civil No. 252-73. Federal District Court of Puerto Rico, August 15, 1978.

Continental Shelf Associates, Inc. 1987. *Southwest Florida shelf regional biological communities survey*. OCS Study MMS 86-0108, 86-0109, and 86-0110. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Cubit, J. D., and J. M. Burgett. In press. Algal blooms after natural disturbances and an oil spill on Galeta Reef, Panama. *Mar. Ecol. Prog. Ser.*

Cubit, J. C., C. D. Getter, J. B. C. Jackson, S. D. Garrity, H. M. Caffey, R. C. Thompson, E. Weil, and M. Marshall. 1987. An oil spill affecting coral reefs and mangroves on the Caribbean coast of Panama. In *Proceedings, 1987 Oil Spill Conference*, 401-406. Washington, DC: American Petroleum Institute.

Danek, L. J., and G. S. Lewbel, ed. 1986. *Southwest Florida shelf benthic communities study. Year 5 annual report*. OCS Study MMS 86-0074, 86-0075, and 86-0076. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Davis, G. E. 1982. A century of natural change in coral distribution at the Dry Tortugas: A comparison of reef maps from 1881 and 1976. *Bull. Mar. Sci.* 32:608-623.

Davis, G. E., and J. W. Dodrill. 1989. Recreational fishery and population dynamics of spiny lobsters, *Panulirus argus* in Florida Bay, Everglades National Park, Florida. Bull. Mar. Sci. 44:78-88.

Davis, G. E., and M. C. Whiting. 1977. Loggerhead sea turtle nesting in Everglades National Park, Florida, U.S.A. *Herpetologica* 33:18-28.

den Hartog, C., and R. P. W. M. Jacobs. 1980. Effects of the '*Amoco Cadiz*' oil spill on an eelgrass community at Roscoff (France) with special reference to the mobile benthic fauna. *Helgol. wiss. Meeresunters.* 33:182-191.

Dennis, J. V. 1959. *Oil pollution survey of the U.S. Atlantic coast*. Washington, DC: American Petroleum Institute.

Diaz-Piferrer, M. 1962. The effects of an oil spill on the shore of Guanica, Puerto Rico (Abstract). In *Assoc. Island Mar. Labs., 4th Meeting, Curacao, 18-20 Nov. 1962*, 12-13.

Diaz-Piferrer, M. 1964. The effects of an oil spill on the shore of Guanica, Puerto Rico (Abstract). *Deep-Sea Res.* 11(5):855-856.

Dodge, R. E., T. D. Jickells, A. H. Knap, S. Boyd, and R. P. M. Bak. 1984. Reef-building coral skeletons as chemical pollution (phosphorus) indicators. *Mar. Pollut. Bull.* 15:178-187.

Drew, R. D., and N. S. Schomer. 1984. *An ecological characterization of the Caloosahatchee River/Big Cypress watershed*. FWS/OBS-82/58.2. Washington, DC: U.S. Fish and Wildlife Service.

Eisler, R. 1975. Acute toxicities of crude oils and oil-dispersant mixtures to Red Sea fishes and invertebrates. *Isr. J. Zool.* 24:16-27.

Enos, P. 1989. Islands in the bay. *Bull. Mar. Sci.* 44:365-386.

Environmental Science and Engineering, Inc., LGL Ecological Research Associates, Inc., and Continental Shelf Associates, Inc. 1987. *Southwest Florida shelf ecosystems study data synthesis report*. OCS Study MMS 87-0023. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Fishelson, L. 1973. Ecology of coral reefs in the Gulf of Aquaba (Red Sea) influenced by pollution. *Oecologia* 12:55-67.

Fishelson, L. 1977. Stability and instability of marine ecosystems, illustrated by examples from the Red Sea. *Helgol. wiss. Meeresunters.* 30:18-29.

Florida Game and Fresh Water Fish Commission. 1989. Official list of endangered and potentially endangered flora and fauna in Florida. Tallahassee.

Fritts, T. H., and M. A. McGehee. 1981. *Effects of petroleum on the development and survival of marine turtle embryos*. FWS/OBS-82/37. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Fritts, T. H., A. B. Irvine, R. D. Jennings, L. A. Collum, W. Hoffman, and M. A. McGehee. 1983. *Turtles, birds, and mammals in the northern Gulf of Mexico and nearby Atlantic waters*. FWS/OBS-82/65. Washington, DC: U.S. Fish and Wildlife Service, Division of Biological Services.

Fucik, K. W., T. J. Bright, and K. S. Goodman. 1984. Measurements of damage, recovery, and rehabilitation of coral reefs exposed to oil. In *Restoration of habitats impacted by oil spills*, ed. J. Cairns, Jr. and A. L. Buikema, 115-179.

Ganning, B., D. J. Reish, and D. Straughan. 1984. Recovery and restoration of rocky shores, sandy beaches, tidal flats, and shallow subtidal bottoms impacted by oil spills. In *Restoration of habitats impacted by oil spills*, ed. J. Cairns, Jr. and A. L. Buikema, 7-36.

Geraci, J. R. 1988. Physiologic and toxicologic effects on cetaceans. In *Synthesis of effects of oil on marine mammals*, ed. J. R. Geraci and D. J. St. Aubin, 168-202. OCS Study MMS 88-0049. Herndon, VA: U.S. Department of the Interior, Minerals Management Service.

Geraci, J. R., and D. J. St. Aubin. 1982. *Study of the effects of oil on cetaceans*. Contract No. AA551-CT9-29. Washington, DC: U.S. Department of the Interior, Bureau of Land Management.

Getter, C. D. 1983. *A laboratory determination of the sensitivity of mangrove seedlings to oil and dispersant combinations*. Report prepared for the Exxon Oil Spill Chemicals, Fate and Effects Environmental Subcommittee, by Research Planning Institute, Columbia, SC. RPI/R/82/10/28-30.

Getter, C. D., and T. G. Ballou. 1985. Field experiments on the effects of oil and dispersant on mangroves. In *Proceedings, 1985 Oil Spill Conference*, 577-582. Washington, DC: American Petroleum Institute.

Getter, C.D., S.C. Snedaker, and M.S. Brown. 1980a. *Assessment of biological damages at Howard Star oil spill site, Hillsborough Bay and Tampa Bay, Florida*. Tallahassee: Florida Department of Natural Resources.

Getter, C. D., J. M. Nussman, E. R. Gundlach, and G. I Scott. 1980b. *Biological changes of mangroves and sand beach communities at the Peck Slip oil spill site, eastern Puerto Rico*. Report prepared for the National Oceanic and Atmospheric Administration, Office of Marine Pollution Assessment, Boulder, CO by Research Planning Institute, Columbia, SC. RPI/R/80/2/18-6.

Getter, C. D., J. Michel, G. I. Scott, and J. L. Sadd. 1981. *The sensitivity of coastal environments and wildlife to spilled oil in South Florida*. Miami: South Florida Regional Planning Council.

Getter, C. D., J. Michel, G. I. Scott, J. L. Sadd, and T. G. Ballou. 1983. *The sensitiviy of coastal environments and wildlife to spilled oil in South Florida (including Broward, Dade, and Monroe Counties)*. Columbia, SC: Research Planning Institute.

Getter, C. D., G. Cintron, B. Dicks, R. Lewis, and E. D. Seneca. 1984. The recovery and restoration of salt marshes and mangroves following an oil spill. In *Restoration of habitats impacted by oil spills*, ed. J. Cairns, Jr. and A. L. Buikema, 65-113.

Gilfillan, E. S., D. S. Page, R. P. Garber, S. Hansen, J. Cooley, and J. Hotham. 1981. Fate of the *Zoe Colocotronis* oil spill and its effects on infaunal communities associated with mangroves. In *Proceedings, 1981 Oil Spill Conference*, 353-360. Washington, DC: American Petroleum Institute.

Gooding, R. M. 1971. Oil pollution on Wake Island from the tanker *R. C. Stoner*. *Spec. Sci. Rep. U.S. Fish Wildl. Serv. (Fish.)* 636:1-10.

Governor's Office of Planning and Budgeting. 1988. *Draft report: Scientific review of environmental studies conducted by the U.S. Department of the Interior in consideration of oil and gas drilling off Southwest Florida*. A report to the Honorable Bob Martinez, Governor of Florida.

Green, R. H. 1979. *Sampling design and statistical methods for environmental biologists*. New York: John Wiley and Sons.

Gundlach, E. R., G. I. Scott, and W. P. Davis. 1979a. *Preliminary assessment of the Howard Star oil spill site, Tampa Bay, Florida*. Report prepared for the Regional Response Team.

Gundlach, E. R., J. Michel, G. I. Scott, M. O. Hayes, C. D. Getter, and W. P. Davis. 1979b. Ecological assessment of the *Peck Slip* (19 December 1978) oil spill in eastern Puerto Rico. In *Proceedings, Ecological Damage Assessment Conference*, 303-317. Arlington: Society of Petroleum Industry Biologists.

Gundlach, E. R., K. L. Finkelstein, and J. L. Sadd. 1981. Impact and persistence of *Ixtoc I* oil on the South Texas coast. In *Proceedings, 1981 Oil Spill Conference*, 477-485. Atlanta: U.S. Environmental Protection Agency, American Petroleum Institute, and U.S. Coast Guard.

Guzman, H. M., J. B. C. Jackson, and E. Weil. In review. Ecological effects of a major oil spill on Panamanian subtidal reef corals.

Hall, R. J. 1980. Effects of environmental contaminants on reptiles: A review. *Spec. Sci. Rep. U.S. Fish Wildl. Serv. (Wildl.)* 28:1-12.

Harrigan, P., J. C. Zieman, and S. A. Macko. 1989. The base of nutritional support for the gray snapper (*Lutjanus griseus*): An evaluation based on a combined stomach content and stable isotope analysis. *Bull. Mar. Sci.* 44:65-77.

Hayes, M. O., E. R. Gundlach, and C. D. Getter. 1980. Sensitivity ranking of energy port shorelines. Preprint from *Proceedings, Energy Ports Conference*. Norfolk: American Society of Chemical Engineers.

Hayes, T. M. 1977. Sinking of tanker *St. Peter* off Columbia. In *Proceedings, 1977 Oil Spill Conference*, 289-291. API Publ. No. 4284. Washington, DC: American Petroleum Institute.

Hettler, W. F., Jr. 1989. Food habits of juveniles of spotted seatrout and gray snapper in western Florida Bay. *Bull. Mar. Sci.* 44:155-162.

Holmquist, J. G., G. V. N. Powell, and S. M. Sogard. 1989. Decapod and stomatopod communities of seagrass-covered mudbanks in Florida Bay: Inter- and intra-bank heterogeneity with special reference to isolated subenvironments. *Bull. Mar. Sci.* 44(1):251-262.

Holt, S., S. Rabalais, N. Rabalais, S. Cornelius, and J. S. Holland. 1978. Effects of an oil spill on salt marshes at Harbor Island, Texas. 1. Biology. In *Conference on Assessment of Ecological Impacts of Oil Spills*, 345-252. Arlington: American Institute of Biological Sciences.

Hudson, J. H., G. V. N. Powell, M. B. Robblee, and T. J. Smith. 1989. A 107-year-old coral from Florida Bay: Barometer of natural and man-induced catastrophes? *Bull. Mar. Sci.* 44(1):283-291.

Hughes, D. 1974. *Sygna* slick. *Mar. Pollut. Bull.* 5:99.

Irvine, A. B., and H. W. Campbell. 1978. Aerial census of the West Indian Manatee, *Trichechus manatus*, in the southeastern United States. *J. Mammal.* 59:613-617.

Irvine, A. B., J. E. Caffin, and H. I. Kochman. 1981. *Aerial surveys for manatees and dolphins in western peninsular Florida, with notes on sightings of sea turtles and crocodiles*. FWS/OBS-80/50. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Jaap, W. 1984. *The ecology of the South Florida coral reefs: A community profile*. FWS/OBS-82/08. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Jaap, W. C., W. G. Lyons, P. Dustan, and J. C. Halas. 1989. Stony coral (Scleractinia and Milleporina) community structure at Bird Key Reef, Ft. Jefferson National Monument, Dry Tortugas, Florida. *Fla. Mar. Res. Publ.* 46:1-31.

Jackson, J. B. C., J. D. Cubit, B. D. Keller, V. Batista, K. Burns, H. M. Caffey, R. L. Caldwell, S. D. Garrity, C. D. Getter, C. Gonzalez, H. M. Guzman, K. W. Kaufmann, A. H. Knap, S. C. Levings, M. J. Marshall, R. Steger, R. C. Thompson, and E. Weil. 1989. Ecological effects of a major oil spill on Panamanian coastal marine communities. *Science* 243:37-44.

Jacobs, R. P. W. M. 1980. Effects of the '*Amoco Cadiz*' oil spill on the seagrass community at Roscoff with special attention to the benthic infauna. *Mar. Ecol. Prog. Ser.* 2:207-212.

Jagtap, T. G., and A. G. Untawale. 1980. Effect of petroleum products on mangrove seedlings. *Mahasagar Bull. Natl. Inst. Oceanogr.* 13(2):165-172.

Jernelov, A., and O. Linden. 1980. The effects of oil pollution on mangroves and fisheries in Ecuador, Columbia. Program of the Second International Symposia on Biology and Management of Mangroves and Tropical Shallow Water Communities, Papua, New Guinea.

Jernelov, A., O. Linden, and J. Rosenblum. 1976. *The St. Peter oil spill--An ecological and socio-economic study of effects*. Publ. B334. Stockholm: Swedish Water and Air Pollution Research Institute.
Johannes, R. E. 1975. Pollution and degradation of coral reef communities. In *Tropical marine pollution*, ed. E. J. Ferguson Wood and R. E. Johannes, 13-51. Amsterdam: Elsevier Oceanography Series, 12.
Johannes, R. E., J. Maragos, and S. L. Coles. 1972. Oil damages to corals exposed to air. *Mar. Pollut. Bull.* 3:29-30.
Kale, H. W. II, and D. S. Maehr. 1990. *Florida's birds: A handbook and reference*. Sarasota: Pineapple Press.
Keller, C. E., and J. K. Adams, ed. 1983. *Proceedings of a workshop on cetaceans and sea turtles in the Gulf of Mexico: Study planning for effects of outer continental shelf development*. New Orleans: U.S. Fish and Wildlife Service.
Knap, A. H. 1987. Effects of chemically dispersed oil on the brain coral, *Diploria strigosa*. *Mar. Pollut. Bull.* 18:119-122.
Knap, A. H., T. D. Sleeter, R. E. Dodge, S. C. Wyers, H. R. Firth, and S. R. Smith. 1983. The effects of oil spills and dispersant use on corals, a review and multidisciplinary experimental approach. *Oil Petrochem. Pollut.* 3:157-169.
Knap, A. H., S. C. Wyers, R. E. Dodge, T. D. Sleeter, H. R. Firth, S. R. Smith, and C. B. Cook. 1985. The effects of chemically and physically dispersed oil on the brain coral *Diploria strigosa* (Dana) - A summary review. In *Proceedings, 1985 Oil Spill Conference*, 547-551. Washington, DC: American Petroleum Institute.
Lai, H.-C., and M.-C. Feng. 1985. Field and laboratory studies on the toxicity of oils to mangroves. In *Proceedings, 1985 Oil Spill Conference*, 539-546. Washington, DC: American Petroleum Institute.
Layne, J. N., ed. 1978. *Rare and endangered biota of Florida. Vol. I. Mammals*. Gainesville: Univ. Presses of Florida.
Leber, K. M. 1983. Feeding ecology of decapod crustaceans and the influence of vegetation on foraging success in a subtropical seagrass meadow. Ph.D. diss., Florida State Univ., Tallahassee, Florida.
Le Gore, R. S., D. S. Marszalek, J. E. Hoffman, and J. E. Cuddleback. 1983. A field experiment to assess impact of chemically dispersed oil on Arabian Gulf corals. In *Middle East Oil Technology Conference, Bahrain*, 51-60. Soc. Pet. Eng. Publ., SPE-11444.
Lewis, R.R. 1979a. Oil and mangrove forests: The aftermath of the *Howard Star* oil spill. *Fla. Sci.* 42(Suppl.):26.
Lewis, R.R. 1979b. Large scale mangrove restoration on St. Croix, U.S. Virgin Islands. In *Proceedings, Sixth Annual Conference on Restoration and Creation of Wetlands*, ed. D.P. Cole, 231-242. Tampa: Hillsborough Community College.
Lewis, R. R. 1980a. Oil and mangrove forests: Observed impacts 12 months after the *Howard Star* oil spill. *Fla. Sci.* 43 (Suppl.):23.
Lewis, R. R. 1980b. Impact of oil spills on mangrove forests. In *Second International Symposia on the Biology and Management of Mangroves and Tropical Shallow Water Communities*, 20 July-2 Aug. 1980, Port Moresby, Madang. Papua, New Guinea.
Lewis, R. R. III. 1983. Impact of oil spills on mangrove forests. In *Biology and ecology of mangroves*, ed. H. J. Teas, 171-183. The Hague: Dr. W. Junk Publishers.
Lewis, R. R., and K. C. Haines. 1980. Large scale mangrove restoration on St. Croix, U.S. Virgin Islands. II. Second Year. In *Proceedings, Seventh Annual Conference on the Restoration and Creation of Wetlands*, 137-148. Tampa: Hillsborough Community College.
Lindberg, W. J. and M. J. Marshall. 1984. *Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (South Florida)--stone crab*. FWS/OBS-82/11.21. Washington, DC: U.S. Fish Wildlife Service.
Lopez, J. M. 1978. Ecological consequences of petroleum spillage in the coastal waters of Puerto Rico. In *Proceedings, Conference on Assessment of Ecological Impacts of Oil Spills*, 895-908. NTIS AD-A072 859. Springfield: National Technical Information Service.
Loya, Y. 1975. Possible effects of water pollution on the community structure of Red Sea corals. *Mar. Biol.* 29:177-185.
Loya, Y. 1976. Recolonization of Red Sea corals affected by natural catastrophes and man-made perturbations. *Ecology* 57(2):278-289.
Loya, Y., and B. Rinkevich. 1979. Abortion effect in corals induced by oil pollution. *Mar. Ecol. Prog. Ser.* 1(1):77-80.
Loya, Y., and B. Rinkevich. 1980. Effects of oil pollution on coral reef communities. *Mar. Ecol. Prog. Ser.* 3(2):167-180.
Lugo, A. E., G. Cintron, and C. Goenaga. 1981. Mangrove ecosystems under stress. In *Stress effects on natural ecosystems*, ed. G.W. Barrett and R. Rosenberg, 129-153. London: John Wiley & Sons Ltd.
Mackin, P. 1950. Effects of crude oil and bleedwater on oysters and aquatic plants. College Station, TX: Texas A&M Univ. Research Foundation. Unpubl. manuscript.
Marshall, M. J. 1985. Stability in an assemblage of caridean and penaeid shrimps inhabiting an intertidal *Thalassia* bed. Ph.D. diss., Univ. of Florida.
Marshall, M. J., and V. Batista. In prep. Ecological effects of a major oil spill on Panamanian subtidal seagrass meadows: An initial look.
Mazzotti, F. J. 1989. Factors affecting the nesting success of the American crocodile, *Crocodylus acutus*, in Florida Bay. *Bull. Mar. Sci.* 44:220-228.
McMillan, C. 1974. Salt tolerance of mangroves and submerged aquatic plants. In *Ecology of halophytes*, ed. R. J. Reimold and W. H. Queen, 379-390. New York: Academic Press.
Minerals Management Service. 1987. *Final environmental impact statement. Proposed oil and gas lease sale 113/115/116*. OCS EIS MMS 87-0019. New Orleans: U.S. Department of the Interior, Minerals Management Service.
Minerals Management Service. 1989. Proceedings of the Gulf of Mexico Sea Turtles and Marine Mammals Workshop. Unpubl. document. New Orleans.
Nadeau, R. J., and E. T. Bergquist. 1977. Effects of the March 18, 1973 oil spill near Cabo Rojo, Puerto Rico on tropical marine communities. In *Proceedings, 1977 Oil Spill Conference*, 535-542. Washington, DC: American Petroleum Institute.
National Research Council. 1985. *Oil in the sea: Inputs, fates, and effects*. Washington, DC: National Academy Press.

National Research Council. 1989. *The adequacy of environmental information for outer continental shelf oil and gas decisions: Florida and California.* Washington, DC: National Academy Press.
National Response Team. 1989. *The Exxon Valdez oil spill: A report to the President.* Washington, DC: U.S. Department of Transportation and U.S. Environmental Protection Agency.
Nelson-Smith, A. 1973. *Oil pollution and marine ecology.* New York: Plenum.
Odum, H. T. 1972. An energy circuit language for ecological and social systems: Its physical basis. In *Systems analysis and simulation in ecology, Vol. II,* ed. B. Patten, 139-211. New York: Academic Press.
Odum, W. E., and R. E. Johannes. 1975. The response of mangroves to man-induced environmental stress. In *Tropical marine pollution,* ed. E. J. F. Wood and R. E. Johannes, 52-62. Amsterdam: Elsevier.
Odum, W. E., C. C. McIvor, and T. J. Smith III. 1982. *The ecology of the mangroves of South Florida: A community profile.* FWS/OBS-81/24. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.
Ogden, J. C. 1977. A preliminary report of a study of Florida Bay ospreys. In *Proceedings, transactions of the North American osprey research conference,* ed. J. C. Ogden, 143-152. Washington, DC: National Park Service.
Oil Spill Intelligence Report (OSIR). 1980a. *Nigeria plans clean-up inspection following well blow-out, 7 March 1980.* Boston: Cahners Publishing.
Oil Spill Intelligence Report (OSIR). 1980b. *Texaco supplies food to Nigerian villages, 18 April 1980.* Boston: Cahners Publishing.
Page, D. S., D. W. Mayo, J. F. Cooley, and E. Sorenson. 1979. Hydrocarbon distribution and weathering characteristics at a tropical oil spill site. In *Proceedings, 1979 Oil Spill Conference,* 709-712. Washington, DC: American Petroleum Institute.
Palik, T. F., and R. R. Lewis III. 1983. *Southwestern Florida ecological characterization: An ecological atlas.* Map narratives. FWS/OBS-83/47. U.S. Fish and Wildlife Service, Division of Biological Services.
Petroleum Industry Response Organization Steering Committee. 1990. *Steering committee report and recommendations on the implementation of PIRO.* Washington, DC.
Rinkevich, B., and Y. Loya. 1977. Harmful effects of chronic oil pollution on a Red Sea scleractinian coral population. In *Proceedings, Third International Coral Reef Symposium, Vol. 2, Geology,* ed. D. L. Taylor, 585-591. Miami: Rosenstiel School of Marine and Atmospheric Science, Univ. of Miami.
Rinkevich, B., and Y. Loya. 1979. Laboratory experiments on the effects of crude oil on the Red Sea coral *Stylophora pistillata. Mar. Pollut. Bull.* 10(11):328-330.
Robertson, W. B., Jr. 1964. Unpublished National Park Service memorandum dated 14 January 1964, describing effects of an oil spill at Fort Jefferson National Monument. Homestead, FL.
Robinson, J. H., ed. 1979. *The Peck Slip oil spill, a preliminary scientific report.* NOAA Spec. Rep. Boulder: U.S. Department of Commerce, Office of Marine Pollution Assessment.
Russell, D. J., and B. A. Carlson. 1978. Edible-oil pollution on Fanning Island. *Pac. Sci.* 32:1-15.
Rutherford, E. S., T. W. Schmidt, and J. T. Tilmant. 1989a. Early life history of spotted seatrout (*Cynoscion nebulosis*) and gray snapper (*Lutjanus griseus*) in Florida Bay, Everglades National Park, Florida. *Bull. Mar. Sci.* 44:49-64.
Rutherford, E. S., J. T. Tilmant, E. B. Thue, and T. W. Schmidt. 1989b. Fishery harvest and population dynamics of spotted seatrout, *Cynoscion nebulosis,* in Florida Bay and adjacent waters. Bull. Mar. Sci. 44:108-125.
Rutherford, E. S., J. T. Tilmant, E. B. Thue, and T. W. Schmidt. 1989c. Fishery harvest and population dynamics of gray snapper, *Lutjanus griseus,* in Florida Bay and adjacent waters. Bull. Mar. Sci. 44:139-154.
Rutzler, K., and W. Sterrer. 1970. Oil pollution: Damage observed in tropical communities along the Atlantic seaboard. *BioScience* 20:222-224.
Satchell, M., and B. Carpenter. 1989. A disaster that wasn't. *U.S. News & World Report* 107(11):60-69.
Schomer, N. S., and R. D. Drew. 1982. *An ecological characterization of the lower Everglades, Florida Bay, and the Florida Keys.* FWS/OBS-82/58.1. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.
Shinn, E. A., B. H. Lidz, J. L. Kindinger, and J. H. Hudson. 1989. *A field guide: Reefs of Florida and the Dry Tortugas. A field trip to the modern carbonate environments of the Florida Keys and the Dry Tortugas.* The 28th International Geol. Conference.
Smithsonian Institution. 1971a. *S. I. Event No. 24-70, Oceanic Grandeur Oil Spill, Torres Strait, Australia.* Center for Short-lived Phenomena. Washington, DC.
Smithsonian Institution. 1971b. *S. I. Event No. 186-70.* Center for Short-lived Phenomena. Washington, DC.
Smithsonian Institution. 1973. *S. I. Event No. 1-72, West Fayu Oil Spill, Caroline Islands.* Center for Short-lived Phenomena. Washington, DC.
Snedaker, S. C., and C. D. Getter. 1985. *Coasts: Coastal resources management guidelines. Coastal Publications No. 2, Renewable Resources Information Series.* Washington, DC: U.S. Department of the Interior, National Park Service and U.S. Agency for International Development.
Snedaker, S. C., J. A. Jimenez, and M. S. Brown. 1981. Anomalous aerial roots in *Avicennia germinans* (L.) in Florida and Costa Rica. *Bull. Mar. Sci.* 31(2):467-470.
Sogard, S. M., G. V. N. Powell, and J. G. Holmquist. 1989. Spatial distributions and trends in abundance of fishes residing in seagrass meadows on Florida Bay mudbanks. *Bull. Mar. Sci.* 44(1):179-199.
Spooner, M. F. 1970. Oil spill in Tarut Bay, Saudi Arabia. *Mar. Pollut. Bull.* 1:166-167.
Spooner, M. F., and G. M. Spooner. 1968. *The problem of oil spills at sea, illustrated by the strandings of the general Colocotronis on Eleuthera, Bahamas, March 7, 1968.* Plymouth: Mar. Biol. Ass. U.K.
State of Florida and Minerals Management Service. 1989a. *Southwest Florida OCS drilling impact assessment task force report.* Prepared for the Governor of Florida and the Secretary of the Interior.
State of Florida and Minerals Management Service. 1989b. *Oil spill risk assessment task force report.* Prepared for the Governor of Florida and the Secretary of the Interior.
St. Aubin, D. J., and V. Lounsbury. 1988. Oil effects on manatees: Evaluating the risks. In *Synthesis of effects of oil on marine mammals,* ed. J. R. Geraci and D. J. St. Aubin, 247-258. OCS Study MMS 88-0049. Herndon, VA: U.S. Department of the Interior, Minerals Management Service.
Straughan, D., ed. 1971. *Biological and oceanographical survey of the Santa Barbara Channel oil spill 1969-1970.* Los Angeles: Allan Hancock Foundation, Univ. of Southern California.

Tabb, D. C., and M. A. Roessler. 1989. History of studies on juvenile fishes of coastal waters of Everglades National Park. *Bull. Mar. Sci.* 44(1):23-34.

Teas, H. J., E. O. Duerr, and J. R. Wilcox. 1987. Effects of South Louisiana crude oil and dispersants on *Rhizophora* mangroves. *Mar. Pollut. Bull.* 18:122-124.

Teas, H. J., A. H. Lasday, E. Luque L., R. A. Morales, M. E. de Diego. 1989. Mangrove restoration after the 1986 Refineria Panama oil spill. In *Proceedings, 1989 Oil Spill Conference*, 433-437. Washington, DC: American Petroleum Institute.

The International Tanker Owners Pollution Federation, Ltd. 1986. *Fate of marine oil spills*. Tech. Info. Pap. No. 11. London.

Thomas, C. 1987. Uptake and effects of petroleum hydrocarbons on *Rhizophora mangle* L. M.S. thesis, Univ. of Miami.

Thorhaug, A., and J. Marcus. 1985. Effects of dispersant and oil on subtropical and tropical seagrasses. In *Proceedings, 1985 Oil Spill Conference*, 497-499. Washington, DC: American Petroleum Institute.

Thorhaug, A., and J. Marcus. 1987a. Oil spill clean-up: The effect of three dispersants on three subtropical/tropical seagrasses. *Mar. Pollut. Bull.* 18:124-126.

Thorhaug, A., and J. H. Marcus. 1987b. Effects of seven dispersants on growth of three subtropical/tropical Atlantic seagrasses. In *Fate and effects of oil in marine ecosystems*, ed. J. Kuiper and W. J. Van den Brink. Dordrecht: Martinus Nijhoff Publishers.

Thorhaug, A., and J. H. Marcus. 1987c. Preliminary mortality effects of seven dispersants on subtropical/tropical seagrasses. In *Proceedings, 1987 Oil Spill Conference*, 223-224. Washington, DC: American Petroleum Institute.

Thorhaug, A., J. Marcus, and F. Booker. 1986. Oil and dispersed oil on subtropical and tropical seagrasses in laboratory studies. *Mar. Pollut. Bull.* 17:357-361.

Tilmant, J. T., E. S. Rutherford, and E. B. True. 1989. Fishery harvest and population dynamics of red drum (*Sciaenops ocellatus*) from Florida Bay and adjacent waters. *Bull. Mar. Sci.* 44:126-138.

Tosterson, T. R., et al. 1977. *Bahia Sucia: A re-evaluation of the biota affected by petrochemical contamination in March 1973*. Univ. of Puerto Rico, Department of Marine Science, C.A.A.M.

U.S. Coast Guard. 1959. Efforts to reduce oil pollution. *Proc. Merchant Mar. Counc.* 16:199-203.

U.S. Coast Guard. 1969. *Sunken tanker project report*. Washington, DC.

U.S. Fish and Wildlife Service. 1980. *Selected vertebrate endangered species of the United States - West Indian Manatee*. FWS/OBS-80/01.35. Washington, DC: U.S. Fish and Wildlife Service.

Vandermeulen, J. H., and E. S. Gilfillan. 1984. Petroleum pollution, corals and mangroves. *Mar. Technol. Soc. J.* 18:62-72.

VAST/TRC. 1976. Oil spill - Bahia Sucia, Puerto Rico, 18 March 1973: Environmental effects. U.S. Environmental Protection Agency Contract No. 68-10-0542.

Williams, J., W. F. Grey, E. B. Murphy, and J. J. Crane. 1977. Drift bottle analyses of eastern Gulf of Mexico surface circulation. *Mem. Hourglass Cruises*, Vol. IV, Pt. 3.

Wilson, K. A. 1989. Ecology of mangrove crabs: Predation, physical factors and refuges. *Bull. Mar. Sci.* 44(1):263-273.

Witham, R. 1978. Does a problem exist relative to small sea turtles and oil spills? In *Proceedings of the Conference on Assessment of Ecological Impacts of Oil Spills, 14-17 June 1978, 629-632*. American Institute of Biological Sciences.

Zieman, J. C. 1982. *The ecology of seagrasses of South Florida: A community profile*. FWS/OBS-82/25. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

CHAPTER 16
SOCIOECONOMIC EFFECTS OF OCS OIL AND GAS DEVELOPMENT

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INTRODUCTION

This chapter analyzes the benefits and costs of outer continental shelf (OCS) oil and gas development and production in the South Florida study area using the findings of economic studies conducted in Florida and other areas. Adjustments of these findings to the particular characteristics of the study area have been made wherever possible. All monetary measures of benefits and costs have been adjusted to a 1987 basis (in dollar values). The data and analyses presented in **Chapter 11** (describing the socio-economic characteristics of the study area) are incorporated in this chapter.

As noted in a recent report issued by a committee appointed by the National Research Council (NRC), there has been little or no study of the sociological effects of OCS development such as that being considered for the study area (NRC 1989). Thus, the present chapter must be considered as an analysis of economic effects. Social effects are included only insofar as they relate directly to economic outcomes.

The approach of the chapter will be to describe and then evaluate (in monetary terms where possible) the major categories of benefits and costs which would be expected to flow to the U.S. society generally and the State of Florida in particular (as the directly affected region) as a result of development and production of the oil and gas resources currently estimated to be recoverable within the study area. This will be done using a conventional benefit-cost framework where benefits and then costs will identified and evaluated. A summary of the estimated net benefits and costs will be

presented at the conclusion of the chapter, along with a discussion of some important categories of costs for which no data currently exist. The chapter begins by presenting an overview of the national significance of the OCS leasing question.

The OCS is one of the Nation's most valuable natural resources, supplying about one-eighth of U.S. crude oil production and nearly one-fourth of U.S. natural gas production in recent years (Minerals Management Service [MMS] 1987b, Appendix F).

The South Florida OCS includes some highly regarded frontier areas. The Eastern Gulf of Mexico Planning Area in total (part of which is included within the study area--see **Chapter 12**) ranked third among 26 Planning Areas in industry interest for leasing, whereas the Straits of Florida Planning Area ranked 20th (MMS 1987b, Table 13.3). MMS risked estimates[1] in mid-1987 of the resource potential of the two Planning Areas combined were put at a total of 250 million barrels of oil and 240 million barrels (oil equivalent) of gas, for a total of 490 million barrels of oil and gas (oil equivalent), assuming a $29 per barrel oil price (MMS 1987b, p. G-57). Total resource estimates for the entire Eastern Gulf of Mexico Planning Area were increased in July 1989 to 1.25 billion barrels of oil and gas (oil equivalent), with about half of this total expected to be recoverable from the area south of 26°N (excluding the study area). There is a 99% probability of commercial hydrocarbons in the Eastern Gulf of Mexico Planning Area south of 26°N, according to this latest estimate (MMS 1989a). Also in 1989, resource estimates for the Straits of Florida Planning Area were revised to 79 million barrels of oil and gas (oil equivalent). Recent estimates by oil industry geologists suggest that potential reserves in the South Florida Basin could be much higher--as much as 7 billion barrels of oil and gas (oil equivalent) (Schanck 1989).

Following its legislative mandate, the U.S. Department of the Interior (USDOI) wishes to maintain the schedule of leasing and exploratory drilling in the South Florida Basin in order to determine the true size of the oil and gas reserves that may be found there and in the hope of obtaining additional domestic energy supplies from this area of the OCS. Officials of the State of Florida, on the other hand, acting as stewards of the unique environmental resources found in the South Florida area (particularly in the Florida Keys), are concerned that drilling and production of oil from the South Florida Basin could, in the event of a major oil drilling accident, expose the State to severe environmental and economic damages. Thus, there is a major conflict of goals between the national interest in enhancing domestic energy supply from renewed OCS leasing and the State of Florida's desire to protect its environment and its economic base in the tourism industry.

In the first 14 years of leasing Federal lands offshore for oil and gas development (that is, prior to the Santa Barbara oil spill of January 1969), OCS lease sales were generally supported by the public, particularly in states such as Louisiana and Texas which had already leased substantial offshore acreage for oil and gas development on State lands. In the years since 1969, however, the response to proposed OCS lease sales in other, more pristine areas such as Alaska, California, and Florida has been mainly critical. This has been reflected in Congressional actions such as Federal regulations requiring the USDOI to balance energy resource development with protection of human,

[1]The MMS issues both *conditional* and *risked* resource estimates. Conditional estimates hinge on the condition that economically recoverable hydrocarbons are present. The likelihood of this condition is termed the marginal probability of commercial hydrocarbons. A risked estimate is produced by multiplying the conditional estimate by the marginal probability of commercial hydrocarbons. Only risked estimates are used in this chapter; conditional estimates are presented in **Chapter 12**. Oil resources are customarily expressed in barrels (1 barrel = 42 U.S. gallons or about 160 L) and gas resources in cubic feet (1 cubic foot = 0.028 cubic meters). Gas volumes have been converted to barrels of oil equivalent by dividing cubic feet by 5,620.

marine, and coastal environments (OCS Lands Act Amendments of 1978, Sec.102 (2)(B)) and moratoria on OCS leasing in environmentally sensitive areas, which have in recent years affected over 50 million acres of Federal lands offshore.

The public's perception of large potential economic and environmental costs of OCS oil development has heightened in the past year in the wake of widely-publicized incidents of pollution of U.S. coastal waters from non-oil sources such as untreated sewage and hospital wastes, together with major oil spills resulting from tanker accidents, particularly the *Exxon Valdez*. This rising level of concern makes it difficult for the public to see that there is a national interest in continued development of OCS lands as a major economic asset whose efficient utilization contributes to economic growth, national security, and the improvement of real income for all Americans, assuming that OCS development is carried out in an environmentally safe manner.

A common misconception reflected in criticism of plans for additional OCS leasing is that only oil companies benefit from these leasing programs. In fact, the benefits of OCS leasing and development are national in scope. That is, under the competitive bidding system that has governed OCS leasing since 1953, the Federal government has collected the net economic value (or economic rent) derived from the oil and gas resources on OCS lands in the form of bonus bids, royalties, and rent payments from companies that lease OCS lands. These Federal revenues reduce the net tax burden of all Americans. At the same time, a large part of the net profits of oil companies is distributed to U.S. stockholders (including pension and mutual funds) or is reinvested in the U.S. The Nation also gains as a result of the lessened dependence upon imported oil which increased production from the OCS provides. Also, many tankers that would carry imported oil into U.S. ports and thus expose the local area to the risks of tanker spillage are "backed out" (or are not needed) because of production of oil and gas from OCS leases. These benefits of oil and gas production from the OCS flow to all regions of the country.

The costs of OCS development, on the other hand, have been disproportionately borne by the regions in which the development has occurred. Concern for the quality of the marine environment is felt not only in coastal states but throughout the country. However, it is still true that people living in coastal states are the most likely to be negatively affected by OCS lease development. Florida feels a particular vulnerability to the risks of offshore oil and gas development. The coastal environment in the South Florida area includes rare or unique ecosystems such as coral reefs, seagrass beds, and mangrove forests. In addition, the economy of Florida is heavily dependent on recreation- and tourism-based industries, together with high quality retirement-residential communities, both of which are based on an image of pristine beaches and pollution-free marine waters.

Thus, the national benefits that would be derived from OCS leasing and development in the South Florida area (only a small proportion of which would accrue to Florida residents) appear small in relation to the potential costs to the State of OCS development, even given very low probabilities of any major OCS-related spills.

The sections that follow will discuss both aspects of the proposed OCS lease sales in the South Florida study area: the benefits to the Nation of additional OCS leasing and development, and the expected environmental and economic costs that are most likely to result from such development.

NATIONAL ECONOMIC BENEFITS OF OCS LEASING IN THE SOUTH FLORIDA STUDY AREA

Economic benefits flow to American society as a result of OCS oil and gas leasing in three major ways: (1) in the form of payments of economic rent (bonuses, royalties, and rentals) to the Federal government; (2) as reductions in the marginal cost of imported crude oil; and (3) through enhancement of national security (including economic security).

Economic Rent

On average for all OCS leases, the market value of expected oil and gas resources exceeds expected costs of production. The difference is referred to as economic rent. Competition among bidders for OCS leases results in the transfer of all or part of this economic rent to the American people as owners of these resources.[2]

Through 1988, lessees of OCS lands had paid the Federal government $151 billion (adjusted to 1987 dollars) in bonus, royalty, and other payments for OCS oil and gas resources, or 42% of the total cumulative production value of these resources (MMS 1989b, pp. 46-47). This amounts to about $15 in (1987 dollars) economic rent for each barrel of oil produced (excluding that portion of OCS economic rent which is directly attributable to natural gas).

The MMS has estimated that net economic value (market value minus costs of production) for the Eastern Gulf of Mexico Planning Area will be about $4 to $5 per barrel, assuming oil prices of $24 to $29 per barrel (MMS 1987b, p. F-75). Because this net value estimate was made on the basis of the much lower (1987) resource estimate for the area, however, and in view of the present, higher resource estimate now accepted by the MMS (1989a), it is reasonable to assume that the new net value estimate for the Eastern Gulf of Mexico Planning Area would also now be much higher, probably on the order of $8 to $10 per barrel. The potential yield of economic rent from the South Florida area cannot be known in the absence of specific knowledge of resource prices and costs of development for this area. But on the basis of historical average yield of economic rent per barrel and the MMS estimate of net economic value (updated to 1989 resource estimates), it is reasonable to put the estimate of potential economic rent from resources developed in the study area at about $8 per barrel (1987 dollars).

Marginal Import Premium on Petroleum

Net imports of petroleum as a percentage of U.S. products supplied amounted to 37% in 1988 and rose above 40% in 1989. The cost of these imports contributed nearly $40 billion to the U.S. trade deficit in 1988 (Energy Information Administration 1989).

For simplicity of analysis, it is often assumed that the elasticity of supply of petroleum imports into the U.S. is very high (or, in other words, that import prices do not rise as U.S. demand for imported oil rises). In fact, given the share of world imports accounted for by the U.S., any increase in U.S. demand for imported oil tends to put upward pressure on the price paid, particularly in the short run.

[2]Economic rent is maximized when competition in the market for leases induces winning bidders to pay all but the necessary costs of production, including a normal profit, over to the lessor (the Federal government). Studies have shown that winning bidders for OCS leases have earned no more than normal rates of return on their OCS lease investments, suggesting that the Federal government has received full economic value for the leases issued (Mead et al. 1986, Table 3-1, p. 53.).

One study of this effect estimated that the "monopsony buying power wedge" for the U.S. was $10.50 per barrel in 1987 prices (Plummer 1981). More recent studies put the marginal import premium (or the excess of import costs per barrel above actual price) in a range from $6 to $124 per barrel, the latter figure including secondary macroeconomic effects (MMS 1987b, p. F-37). Given lower levels of crude oil prices currently, $5 per barrel (1987 dollars) appears to be a conservative estimate of the import premium associated with incremental production of crude oil from the OCS--especially in view of the fact that this premium is attributed to oil production alone when, in fact, both crude oil and natural gas produced from the OCS have the effect of offsetting petroleum imports.

Enhancement of National Security

Two aspects of the national benefits of enhanced domestic energy production are relevant. The first is based strictly on considerations of national defense; the second embraces the broader issue of economic security.

National Defense

Petroleum supply is a critical requirement for a country in a time of war or national emergency. Tax preferences, oil import quotas, and other measures designed to protect the domestic oil industry on national defense grounds have repeatedly been adopted by Congress since the 1920s. More recently, these policies have included the creation of the Strategic Petroleum Reserve (SPR) as part of the Energy Policy and Conservation Act of 1975. The SPR is a stockpile of crude oil that is maintained in order to mitigate the damage that would be caused by an unexpected interruption in the flow of imported petroleum into the U.S.

Economic Security

An interruption in the supply of imported oil has the potential to severely disrupt the functioning of the U.S. economy, as the experience of the period following the Arab oil embargo of 1973 indicates. As previously noted, the potential social costs of interruptions in imports of oil have been estimated to be as high as $124 per barrel, but such estimates are inherently speculative. A lower-bound estimate of the magnitude of the benefits of OCS oil and gas production to U.S. national security (including economic security) may be obtained by assuming that these benefits are at least the same, on a per-barrel basis, as those which are obtained from the SPR itself, or at least equal to the SPR's estimated opportunity cost of about $4 per barrel (1987 dollars) (Griffin and Steele 1986).

This listing of the benefits of enhanced production from the Florida OCS is probably conservative because it ignores benefits of increased productivity of U.S. labor and capital involved in OCS development and makes no allowance for the effect of OCS production on the U.S. balance of payments, both of which would likely result in higher real income for Americans. Furthermore, no account is taken of possible technological spillover benefits from OCS development that could be captured by U.S. oil companies (benefiting the Nation both directly and through enhancement of export income to U.S. oil service companies). Finally, no explicit value is given here to the fact that OCS production reduces the number of tankers bringing imported oil into U.S. ports, thus creating an additional benefit in terms of lowered risk of oil spills from tankers. (Benefits associated with reduced probabilities of oil spills from tankers are included in the USDOI cost/benefit framework; see MMS [1987b], p. G-68).

In summary, a conservative estimate of the benefits of enhanced OCS oil production includes collection of economic rent by the Federal government, reduction in the price premium on imported oil, and national security benefits. Together, these benefit categories amount to about $17 per barrel, on average, expressed in 1987 prices. It must be emphasized that these benefits represent a true social surplus above production costs for the people of the U.S.

THE COSTS OF OCS OIL AND GAS DEVELOPMENT OFFSHORE FLORIDA

The prospective benefits of OCS oil and gas production from the South Florida Basin must be balanced against the estimated external costs and negative regional economic effects of OCS development to determine whether this development is economically justified. Two concepts of cost will be considered in this context. The most important is *social cost*, defined as the opportunity cost to the Nation of such prominent external costs as environmental damage, reductions in the net value of recreation, reductions in commercial fisheries yields, and other market and non-market costs.

The second cost concept is *damage to the regional economy*. Some regional damage costs involve social costs, as would be true if an oil spill damaged commercial fisheries in Florida with attendant losses of catch and value. Other regional damage costs are not social costs because the losses incurred in one region are offset by gains in another area, as would be true if an oil spill reduced tourism in Florida but temporarily diverted the same number of tourist visits to a non-affected area in another state.

Few environmental policy issues have received more comprehensive study in the U.S. than that of offshore leasing and development. Through 1983, the USDOI alone had spent over $340 million on environmental and related studies of offshore development, and planned to continue such studies at the rate of about $20 million per year in succeeding years (MMS 1983, pp. 48, 82, and 121-123). Additional studies of offshore oil and gas development and oil spill effects have been funded by the U.S. Environmental Protection Agency (EPA), the National Oceanic and Atmospheric Administration (NOAA), and other Federal and State agencies.

Despite these extensive research efforts, a committee appointed by the NRC to review the OCS environmental studies program concluded that socioeconomic information for Southwest Florida is not currently adequate, particularly in respect to analyses focused on the human environment, encompassing sociological, political, and psychological effects (NRC 1989). There is no doubt that social impacts of OCS development have not been studied in any detail in Florida. Some aspects of economic damages have also not been studied directly as they relate to OCS leasing, as discussed in the next section. However, other important aspects of economic effects have been studied quite intensively. These studies have focused on the major areas of concern listed below: (1) effects on the natural environment; (2) effects on recreation and tourism; (3) effects on commercial fishing; (4) uncompensated costs of oil spill cleanup; (5) impairment of air quality resulting from production, transportation, or processing of oil and gas; (6) impairment of water quality resulting from disposal of drilling fluids, cuttings, or produced water; (7) effects on property values; and (8) infrastructure costs.

Effects on the Natural Environment

This is the most difficult aspect of damages to attempt to quantify in economic terms, since many would question the validity of any specific dollar value that might be placed on an estuary, a mangrove community, or the life of a seabird or manatee.

Marine biologists carried out extensive studies of damage to the marine environment caused by oil spills such as *Torrey Canyon*, Santa Barbara, *Zoe Colocotroni*, and *Amoco Cadiz*. These studies documented major reductions in population densities for many species of marine plants and animals in the short run. Continuing studies have shown that as time has passed, the marine environment in these areas either recovered or was in the process of recovering.[3]

A more recent major oil spill raises serious concerns for Florida, however. In 1986, more than 50,000 barrels of crude oil were spilled from a ruptured storage tank near the Caribbean entrance to the Panama Canal. As in the case of the *Zoe Colocotroni* spill, there was extensive damage to mangroves, seagrasses, and their related biological communities. In addition, there was extensive mortality of subtidal corals that had not been demonstrated in other oil spills or in laboratory experiments. The injury to corals has allowed colonization of their bare skeleton by other organisms. The injured corals may also be more susceptible to epidemic disease and to grow and reproduce more slowly than uninjured corals, setting off a chain reaction that may continue long after oil is present in the environment (Jackson et al. 1989).

Considerable research has been conducted concerning methods of assessing the social cost arising from injury or death of non-marketed species in the natural environment. One methodology uses a "value in use" approach which evaluates a natural environment in terms of its effects on the food web or as one of the factors responsible for creating recreational opportunities (see, for example, Grigalunas et al. [1988], which uses a simple food web model to simulate damages). This is the approach used by MMS in estimating the environmental costs reported in **Table 16.1** (presented later in this chapter). Another approach attempts to measure the "option," "preservation," or "existence" values that are lost when living organisms are killed or injured as a result of an oil spill. Survey research is used in this case to determine "willingness to accept compensation" or, more likely, "willingness to pay" to avoid the damages suffered when an environmental incident causes death or injury to living things. The results of these surveys are likely to be questioned by many as speculative, however, because no money is actually changing hands and there is an incentive on the part of respondents to exaggerate their concerns when their response is costless.[4]

Some would argue that any approach which attempts to measure the value of the natural environment in terms of dollars is fundamentally flawed. In this view, living organisms have an intrinsic value that cannot be subjected to economic calculation. Such values should more properly be judged in qualitative terms only, without any attempt at translation into dollars. Unfortunately, however, this may leave important aspects of the damage equation out of consideration in practice. It is worth noting, also, that society routinely accepts risk to *human* life in making many policy decisions and has accepted, as well, the appropriateness of economic (or market-based)

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[3]The *Zoe Colocotroni* case is particularly relevant for Florida. Large quantities of crude oil intentionally dumped from a grounded tanker ended up in Bahia Sucia, a bay on the southern coast of Puerto Rico. High levels of animal and plant mortality, particularly within a rich mangrove community, were observed after the spill. After considerable legal action, including appeals to the U.S. Court of Appeals and the U.S. Supreme Court, the Commonwealth of Puerto Rico was given approval for funding of a restoration plan for Bahia Sucia, but by the time a final plan was prepared, the natural environment began to recover. A new mangrove forest appeared, replacing the trees destroyed in the spill. The Commonwealth, therefore, decided to leave the area untouched and to pursue a monetary settlement with the defendants, which was successful. Funds obtained from this settlement have been dedicated to a new marine laboratory (N. Jimenez, pers. comm. 1986, attorney for Environmental Quality Board of Puerto Rico).

[4]A review of some of the methodologies used in evaluating noncommercial marine organisms and their theoretical and practical difficulties is provided in Brown (1983). For a review of research studies using survey approaches to evaluate user and non-user environmental damages, see Desvousges and Skahen (1985).

approaches to evaluating loss of human life. It would seem equally appropriate, then, to accept similar approaches in dealing with death or injury to other living things.

Unfortunately, no economic studies have been conducted (using public opinion surveys) to attempt to put a dollar value on society's willingness to bear the risk of environmental damage resulting from OCS development in the South Florida Basin. We have no data on which to base estimates of the "preservation," "existence," or "option" values associated with such prominent environments as the coral reefs in the study area. Thus, any listing of potential environmental costs of OCS leasing is missing a potentially important element of social cost. New research studies are needed to contribute data and analysis in this area, as suggested in the Conclusions section below.

The MMS (1987a, Vol. 2, Chapter 6) reached the following conclusions concerning the potential for environmental damage from the proposed 5-Year OCS Oil and Gas Leasing Program (5-Year Program) in the Eastern Gulf of Mexico Planning Area: (1) the overall impact in respect to offshore water quality is estimated to be low; (2) the level of impact on plankton is expected to be very low; (3) the level of impact on benthos in general in the Planning Area is expected to be very low; however, in those areas having live bottom, the effect could be very high where anchoring of boats, barges, and drilling rigs occurs; (4) the impact on fish resources is expected to be moderate; (5) the impact on marine mammals is expected to be low; (6) the impact on coastal and marine birds is expected to be low; (7) the impact on endangered and threatened species is expected to be low; (8) the impact on wetlands and coastal seagrasses is expected to be low; and (9) the impact on areas of special concern (specifically, the Florida Middle Ground) could be very high because of risk to the corals.[5]

From the viewpoint of many political leaders in the State of Florida, the central environmental concerns relating to the proposed OCS leasing offshore Florida are these: (1) the oil industry has not demonstrated a present capability to clean up and control a major oil spill in the proposed leasing area; (2) too little is known about the environmental effects of the dispersants (such as Corexit) that might be used to control an oil spill; and (3) too little is known about the long-term effects of oil on fragile marine biological communities such as coral reefs, mangrove forests, and seagrass beds, which are likely to be affected by routine drilling operations as well as oil spills in the proposed lease area. Even if these communities were capable of recovering from oil spill effects over many years, significant damage to society would still have occurred (Martinez 1989; Twachtmann 1989).

In reaction to the *Exxon Valdez* oil spill, a task force has been formed to develop the Petroleum Industry Response Organization (PIRO) (American Petroleum Institute 1989; PIRO Steering Committee 1990). PIRO will be designed to respond to a 216,000-barrel oil spill within five hours in coastal waters in any of five regions in the U.S. (including the Gulf of Mexico), but this response capability will not be in place for at least five years (*Oil and Gas Journal* 1989). This plan is evidence of the seriousness with which the oil industry views the problem of oil spills, but until the plan is implemented and shown to be effective, the State's concern over the ability of oil companies to clean up a major oil spill will continue.

[5]The Florida Middle Ground is a topographic feature located about 160 km (86 nmi) west-northwest of Tarpon Springs. Risk of environmental damage in the Florida Middle Ground led the USDOI to exclude 23 blocks in this area from leasing during all Eastern Gulf of Mexico Planning Area sales in the current 5-Year Program (MMS 1987a).

Effects on Recreation and Tourism

Oil and gas development may adversely affect recreation values for both residents of and visitors to Florida in two ways: (1) by reducing the *number* of recreation visits to an affected area, and (2) by reducing the *value* of the recreation visits which continue to be made to the area. Even though a visit to a beach or a day of recreational fishing may have no admission fee and thus be "free," each visit generally yields a net value above the cost of access to the recreation user. This value is referred to as "consumer's surplus" in economics. When a recreation site is injured by an oil-related incident, a social cost in incurred in the form of a loss of consumer's surplus. Using well-established methods of analysis (such as the travel cost method), economists can estimate the loss in the aggregate value of consumer's surplus caused by such an incident.

In addition to the loss of consumer's surplus caused by an oil-related incident, the reduction in the number of recreation visits may cause a decline in the earnings of tourism-related businesses in the affected area. To the degree that this decline in tourism is offset by an increase in tourism and associated spending in another area within Florida, the net effect on the economy of Florida and on tax collections within the State will be minor, even though the costs to the regional economy may be significant. Only if tourists are diverted to out-of-State recreation sites will there be damage to the State's economy in addition to the loss of consumer's surplus discussed earlier.

Even in the absence of an oil spill, routine and necessary operations of the oil industry involving construction crews, service boats, or the placing of platforms or other structures in an otherwise pristine offshore area may create noise, unsightly visual intrusions, or other interference with the peaceful enjoyment of marine recreation. To the degree that these kinds of operations reduce the quality or number of recreation visits, there will be a consequential reduction in consumer's surplus and possibly also damage to the regional economy.

One study of the effects on recreation values of construction and operation activities relating to OCS leasing concluded that a major new OCS development requiring three platforms, two pipelines, and an onshore processing facility near a high-valued beach area in Ventura, California would reduce recreation attendance, spending, and consumer's surplus by 0.1 to 0.4% during the construction phase and by 0.4 to 2.9% in the operations phase (David Dornbusch and Co. 1987). The negative effects on beach-related recreation in South Florida of OCS oil- and gas-related construction and operation in the study area would likely be smaller than those estimated above. The MMS estimated that only two platforms would be built and no pipelines to shore or new onshore processing facilities would be required as a result of leasing in the entire Eastern Gulf of Mexico Planning Area under the current 5-Year Program (MMS 1987a, Appendix K). Leasing in the Straits of Florida Planning Area was projected to result in construction of one platform, a gas pipeline landfall, and an onshore gas plant (MMS 1987a); however, if leasing eventually occurs, the gas pipeline and gas processing plant are unlikely to be located in the study area (see **Chapter 12**).

Marine-related recreation and tourism have great significance for the economy of Florida, as is indicated in a number of recent economic studies:

- About three out of four of the 35 million tourists who visited Florida in 1987 had one of Florida's coastal counties as a primary destination for their trip. These tourists spent about $12 billion in the 35 coastal counties of Florida in that year, contributing 19% of the State sales tax collections made in those counties (Bell 1989).

- Over 5 million people participated in recreational saltwater fishing in Florida in 1980 to 1981. They enjoyed over 58 million fishing days, about 72% of which involved tourists. Recreational fishermen spent about $2.6 billion (1987 dollars) in Florida in the one-year study period, creating 124,000 jobs (Bell et al. 1982).

- In recent years, over 600,000 boats have been registered in Florida, and 1,500 marinas with 10 or more slips were in business to serve the demand for boating. There were also about 1,300 charter boats and other vessels available for hire (Adams 1987). The boat and trailer manufacturing industry, marinas, marine trades and services, and related industries were directly responsible for employing about 23,000 people in Florida in 1985 (Milon and Adams 1987).

- Finally, over 5 million residents and 8 million tourists visited Florida's beaches in 1984, generating 146 million recreation days and creating 180,000 jobs. Beach-related spending generated $164 million in tax revenue for Florida in 1984, or 2.8% of State tax collections in that year (Bell and Leeworthy 1986).

The recreation activities listed above are to a considerable degree overlapping (i.e., visitors to coastal counties are also saltwater fishermen, boat users, etc.). Thus, these estimates of spending and job creation cannot be simply added together. One general conclusion that may be reached, however, is that about 18% of all tourist visits within Florida occur in the study area, and this tourism generates approximately 3.5% of Gross State Product annually (see **Chapter 11**).

Given the magnitude of Florida's recreation and tourism sector and the degree to which it depends on the qualities of beaches and coastal waters, it is easily assumed that a major oil spill would result in serious, long-term injury to an affected coastal region. But the experience of the actual effects of several major oil spills in other areas shows that, in fact, these effects have been minor and of short duration.

The Santa Barbara oil spill in 1969 resulted from an OCS production well blowout that caused 77,000 barrels of oil to be released to the marine environment. A large part of this oil was deposited along 50 km (27 nmi) of coastline in Santa Barbara and Ventura Counties, an area of exceptionally high quality beaches. While tourism declined in the City of Santa Barbara in 1969, studies showed that tourists were mainly diverted to other inland areas of Santa Barbara County. Overall, tourism rose in Santa Barbara County in 1969 (although the total number of tourists was about 5% below the expected number based on growth trends). Analysis showed that those tourists who did not visit Santa Barbara in 1969 were diverted to other California counties whose beaches were not affected by the oil spill and that the normal level of tourism was restored in the county by the third quarter of the year. Thus, the oil spill resulted in no net loss of revenues to the California economy. Based on a recreation survey conducted after the oil spill, it was estimated that the loss of consumer's surplus resulting from the decline in the number and value of beach visits amounted to about $9.5 million (1987 dollars) (Mead and Sorensen 1970).

The *Amoco Cadiz* oil spill in 1978 resulted from the grounding of a tanker on the coast of France. The incident caused 1.6 million barrels of crude oil to be spilled along about 400 km (216 nmi) of the Brittany coastline, a very popular area for ocean-view holidays. The reduction in tourist visits to the affected coastal area in 1978 as compared to 1979 was estimated to be between 5 and 15%, with a 10% reduction in visitors staying in hotels in the area. Almost all of the tourists who did not visit Brittany in

1978 visited another destination site in France instead. Thus, the loss of revenues to the French economy was probably very small. There was no evidence that the oil spill affected tourism in the area in 1979 or later years (Brown et al. 1983).

The 1979 *Ixtoc I* oil spill was caused by an exploratory well blowout in Mexican waters within the Gulf of Mexico that spilled 3 to 5 million barrels of oil before it was controlled. Although major effects on tourism along the Texas Gulf coast near Galveston Island were expected, a study of the effects of the spill on tourism at three coastal Texas State parks found no effects on visitation rates, except those produced by gasoline shortages experienced in this area in the summer of 1979. The study made no attempt to evaluate any possible decline in the quality of recreation visits to the area, however (Freeman et al. 1985). Another study of the effects on tourism of the *Ixtoc I* spill, based on interviews with owners of tourism-related businesses, concluded that the spill had resulted in the loss of about $12 million in tourist sales (Restrepo et al. 1982). This study did not correct for the effects of the gasoline shortages, however, nor was there any independent verification of the losses claimed by the business owners.

In 1967, the *Torrey Canyon* spilled 850,000 barrels of crude oil near the southern coast of England. Researchers in Britain discovered no effects on tourism as a result of the *Torrey Canyon* spill and another major tanker spill (*Newquay*), both of which occurred near important tourist destination sites on the coast of Cornwall. The investigators concluded that "most people accept oil pollution as just another uncertainty relating to a seaside holiday," and that factors such as bad weather or other forms of coastal water pollution, particularly sewage, are "much more significant" than oil pollution in affecting tourism (Royal Commission on Environmental Pollution [RCEP] 1981).

The most relevant of the recreation loss studies cited above in attempting to evaluate the potential cost of an oil spill offshore Florida are the Santa Barbara and the *Amoco Cadiz* studies. Generalizing from these studies, it may be concluded that a major oil spill near a coastal recreation area in Florida would reduce visitation rates in the area by about 5 to 15% over one season but would have no long-term effect on tourism in the area. The reduction in visitation in the affected region would have only a small, temporary effect on the total amount of tourism within Florida because most tourists who did not visit the affected area would be diverted to other non-affected sites within the State. Thus, while private firms located in the affected areas would suffer losses of 5 to 15% as a result of a major oil spill (losses which, in many cases, would be recoverable from the polluting firm or from compensation funds), there would be a much smaller loss of tourist spending within Florida as a whole (as a result of tourists diverted to Caribbean islands, for example). This conclusion assumes, of course, that no permanent injury to Florida's coastal environment would have occurred.

Even temporary environmental damage could create a significant loss of consumer's surplus, however. Based on Wilman's (1984) simulations of the non-market based recreation losses that would be suffered in the event of hypothetical oil spills of 1,000 barrels or 37,500 barrels occurring off the coast of Cape Cod, the USDOI concluded that OCS oil spills of this size could produce damages at Gulf of Mexico sites (reductions in consumer's surplus, in 1987 dollars) amounting to $538 per barrel reaching shore plus $135 per barrel in congestion losses to tourists who were diverted to other sites (MMS 1987b, p. G-36). These estimates (particularly the congestion losses) are probably high for various reasons relating to (1) the assumptions made in the scenarios used by Wilman, and (2) the choice by the authors of the MMS damage assessment report of the range of outcomes to be applied. Assuming these estimates are reliable, however, it may be concluded that an oil spill as large as the Santa Barbara

spill for which the proportion of oil reaching shore is 50% would impose non-market related losses on tourists and residents of Florida of about $26 million.[6]

The oil spill effects on recreation that are cited above are similar in size to those estimated in a recent simulation of a major oil spill on the coast of Orange County, California (an area of high incomes and property values). Assuming a hypothetical oil spill affected summer tourism from Newport to Laguna Beach for a six-week period, this simulation predicted the spill would result in annual declines in boating (10.2%), recreational fishing (7.1)%, beach attendance (from 6.1 to 6.8%), and tourist spending (6.5 to 7.2%). The total losses in consumer's surplus would be $18.3 million (David Dornbusch and Co. 1987, p. 1-15).[7]

The MMS recently initiated a new study of the effects of oil and gas development on recreation and tourism off the Straits of Florida. This study should provide more in-depth analysis of the potential effects of OCS oil and gas activities in this part of the study area on the regional economy.

Effects on Commercial Fishing

Landings of commercial fish and shellfish in Florida in 1988 were valued at $175 million, with about 30% of this total accounted for by ports within the three-county study area (Collier, Monroe, and Dade Counties). The value of seafood sold from processing plants in Florida in 1988 was $516 million, and an estimated 40,000 jobs in Florida are created by the harvesting, processing, and retailing of seafood in Florida (Cato 1989).

Commercial fishermen can be affected in several ways by an oil spill in their fishing area. The oil may come into the ports or harbors where fishing boats are kept, denying them exit onto fishing grounds. Oil in the open seas may also disrupt the natural movements of adult fish and shellfish, diverting them to other areas and away from the fishing grounds used by local fishermen. More seriously, oil may invade nursery areas such as coastal wetlands, damaging eggs and juvenile fish, with negative long-run effects on adult populations. Estimates of the estuarine dependency of sport and commercially harvested fish in Florida range from 85 to 95% of the total value of the fishery catch. Estimates place the capitalized value per acre of wetlands (as habitat) in Florida as high as $9,811 on Florida's east coast and $2,276 on Florida's west coast (Bell 1989).

Damage to commercial fisheries resulting from oil spills has been most carefully documented in the cases of Santa Barbara and *Amoco Cadiz*. In the Santa Barbara case, protective booms were placed across the mouth of the Santa Barbara harbor for a period of about two months, preventing about 75 fishing boats and their crews from working. The total cost to the fishing industry resulting from this enforced idleness was about $2 million (1987 dollars) (Mead and Sorensen 1970). A later study that compared the expected to the actual catch by species in individual fishing zones within the

[6]The likelihood of an OCS well blowout offshore Florida of the size that occurred in Santa Barbara is small for several reasons, including the different geology of the eastern Gulf of Mexico, improvements in drilling techniques, and requirements that OCS wells be fully cased. Over the 18-year period from 1971 to 1988, only 900 barrels of oil were spilled as a result of well blowouts from OCS leases (MMS 1989b, p. 98).

[7]By way of comparison, the South Florida Regional Planning Council (SFRPC) estimated that an oil spill contacting Dade County would result in the loss of 2 million to 4.5 million tourist nights, while an oil spill contacting Monroe County would result in the loss of 0.4 million to 1 million tourist nights, depending on quarter of the year in which the spill occurred (SFRPC 1984, pp. 82-83.). These estimates appear to be high compared to the experience of other recreation areas affected by oil spills. The methodology used to estimate these losses assumed that *all* tourists who would have come to these counties for coastal activities during the affected quarter would stay away in the event of an oil spill, an assumption that is contradicted by experience.

Santa Barbara Channel for the year 1969 showed a statistically significant decline in total catch of about $550,000 (1987 dollars). This loss amounted to <5% of the total catch in the region. There was no evidence of any reduction in expected catch in the time period after 1969 (Sorensen 1975).

Damage to oyster culturing operations located in bays and estuaries heavily damaged by the *Amoco Cadiz* oil spill was significant, amounting to about $43 million (1987 dollars) over the 21-month time period following the oil spill. Open seas fisheries were less severely affected, with total damage amounting to about $8 million (1987 dollars). The expected catch of open seas fisheries declined by about 27% during 1978, while the yield of oyster culture operations was reduced by about one-third over a four-year post-oil spill period. Holding tanks for lobsters and other shellfish that were located in the impact zone suffered losses of $4.6 million (1987 dollars), while the cost of cleaning damaged fishing boats amounted to $0.5 million (Sorensen 1983). Open seas fisheries in the area appeared to have recovered by the eighth month following the oil spill, but damage to oyster culturing continued into the fourth year, illustrating the particular vulnerability of an estuarine habitat to severe oil spillage.

European researchers have studied effects of numerous oil spills on fisheries in the North Sea. Commenting on these studies, the RCEP declared, "we agree with the findings that the effect of oil pollution in general on adult fish populations is so slight as to be undetectable in fishery statistics" (RCEP 1981).

Routine OCS drilling and production operations would be unlikely to have any significant effects on commercial fish catches offshore Florida. A study of conflicts between fishing and oil-related activities concluded that commercial fishing losses resulting from OCS oil and gas development in the eastern Gulf of Mexico would amount to <0.25% annually (Centaur Associates, Inc. 1981, Vol. IV, Exhibit 6-3). Translating this finding to the study area, this would amount to a decline in annual values of commercial fisheries landings of about $150,000 annually.

Because South Florida's coastline is dominated by mangroves, marshes, other estuarine wetlands, and seagrass communities, the commercial fisheries of the three-county study area are probably vulnerable to more significant long-run effects from oil spills than were observed in either the Santa Barbara or the *Amoco Cadiz* incidents.

Uncompensated Costs of Cleanup

Fears that coastal residents or government agencies would be saddled with the costs of cleaning up oil spills left behind by unknown or insolvent parties led to legislation in the early 1970s that resulted in the establishment of oil spill compensation funds in several states (including Florida) and at the Federal level. There have been no significant indemnities paid for oil spill damage resulting from OCS development out of these funds. This result should be expected, since spilled crude oil can be fingerprinted and OCS operators cannot leave the scene of a spill. The Florida Coastal Protection Fund paid only about $20,000 per year in total claims for cleanup and damage from all types of oil spills over a recent six-year period (and none for OCS-related spills). The fund balance was accumulating interest so rapidly in recent years that the Florida Legislature was able to divert part of it to deal with groundwater contamination problems in the State. As a result of the *Exxon Valdez* spill, major revisions in the scope and funding of Federal oil spill compensation funds are under consideration, increasing the likelihood that cleanup costs for future oil spills in U.S. waters will be fully paid by the parties at fault or by the oil transportation industry generally.

In the only major oil spill on record involving OCS drilling (Santa Barbara), the responsible parties (Union Oil Company and its partners) agreed to pay "all costs of cleanup and restoration of the Santa Barbara-Ventura coastline to its original beauty and charm" (Gaines 1969). Over $31 million 1987 dollars were spent by the oil companies in cleanup and restoration efforts, which were considered successful.

Oil companies face strict liability in respect to oil spill cleanup costs; thus, states and local governments are not required to prove negligence in order to recover these costs (or, more likely, to enforce cleanup on an OCS operator). A recent Federal appeals court decision also increases the likelihood that companies responsible for oil spills will be required to restore an affected area. The Federal court of appeals in Washington, DC has rejected a USDOI formula for determining natural resource damages from an oil spill (or other pollution incident) that allowed polluters to pay either the cost of restoring the affected area or the market value of the damaged resources, whichever was less. The court ruled that companies responsible for oil spills should have to pay the full cost of restoring the environment to its condition before the damage occurred, except where restoration is technically infeasible or when the cost of restoration is wholly disproportionate to use value. This ruling is expected to substantially increase the cost to polluters of natural resource damage (*State of Ohio, Petitioner et al. v. U.S. Department of Interior*, cases 86-1529 and 86-1575, decided 14 July 1989).

Impairment of Air Quality

Environmental stipulations attached to OCS leases require use of "best available control technologies" on production, transportation, and storage facilities to protect air quality. The EPA and State pollution control agencies are both involved in developing these rules and in monitoring compliance. They have full access to platforms for purposes of inspection or testing (MMS 1983, pp. 84-85; American Petroleum Institute 1984). Because of recent disputes over air quality impacts of offshore production in the Santa Barbara Channel, it is likely that the EPA will give local environmental agencies a greater role in determining air quality requirements for OCS leases in the future.

After studying the effects on air quality that might result from a proposed lease sale in the Eastern Gulf of Mexico Planning Area, the MMS concluded that the ambient air quality in the region was generally better than National standards; that 19 of the 22 counties bordering the Eastern Gulf of Mexico Planning Area are clean-air counties; and that only one county (Dade) in the study area is a non-attainment area (Primary-Ozone). Everglades National Park has been declared a mandatory "Prevention of Significant Deterioration" (PSD) Class I area by the EPA because visibility is an important value. The area is currently within standards for PSD. Because of prevailing meteorological and other characteristics, the MMS believes that transport of emissions from offshore sites to onshore coastal areas in Florida would be rare. In addition, the State of Florida has a State Implementation Plan for air quality coupled with regulatory enforcement and monitoring programs that would apply to the OCS leases in the study area. The MMS concluded that the overall impact of OCS operations on coastal air quality in expected to be low in Dade and Monroe Counties and very low in Collier County (MMS 1987a, III.B.-37-38 and IV.B.6-5).[8]

[8]Air quality regulations applying to OCS activities are set forth by the MMS (1987a, Vol. 3, Appendix B).

Impairment of Water Quality from Discharge of Drilling Fluids, Cuttings, Produced Water, and Platform Wastes

The effect of drilling fluids and cuttings on the marine environment has been a major concern, leading to research expenditures of about $15 million in recent years. These studies concluded that environmental effects of drilling fluids are localized and temporary (RCEP 1981; MMS 1983; NRC 1983; Engelhardt et al. 1989). Only low-toxicity drilling fluids (all approved by the EPA) are used offshore. Localized turbidity is created by construction and drilling, which would have only a small effect on phytoplankton but which could interfere with the respiratory or feeding mechanisms of other marine organisms within the affected area. The level of turbidity associated with OCS drilling is generally less than that created by conventional dredging or clam harvesting activities. The discharge of produced water and treated sanitary wastes will have only a small effect on water quality in a limited area around a platform. Under EPA regulations, produced water must be treated and separated before it can be reinjected or discharged from a platform. The MMS estimates that the overall impact on offshore water quality from the proposed leasing in the study area will be low (MMS 1987a, IV.B.6.-3).

As noted in **Chapters 12** and **13**, effects of routine discharges in the study area could be lessened or avoided through mitigation measures, including spatial separation of discharges from sensitive ecosystems such as seagrass beds and coral reefs. Based on the record of OCS operations elsewhere in the Gulf of Mexico (e.g., Flower Garden Banks), it is unlikely that unrestricted discharges would be allowed near coral reefs or seagrass beds in the study area.

Effects on Property Values

A study of the economic cost of the Santa Barbara oil spill concluded that property values of private homes in the beachfront area had declined temporarily as a result of the spill, with consequent losses of economic rent to owners amounting to about $3.5 million (1987 dollars) (Mead and Sorensen 1970). A similar analysis of possible losses of property values in the area of Brittany most affected by the *Amoco Cadiz* oil spill showed that no discernible losses had occurred, however (Sorensen 1983). The main reason for the latter conclusion was that only a small number of real estate sales typically take place in the coastal area of Brittany in any one year. It is likely, therefore, that property owners actually suffered temporary losses in implicit rent (or amenity value of private homes) on the same order as the losses observed in Santa Barbara despite the fact that there were too few transactions to document these losses.

The important conclusion from both of these studies is that values of property near the ocean are determined by long-run factors relating to the increasing scarcity of private beachfront locations in desirable areas. After a temporary decline in value in the event of an oil spill, property values in an affected coastal area can be expected to return to their normal levels reflecting the premium associated with their preferred location.

Infrastructure Costs

Any major new OCS development near Florida's coastline may be expected to have some effect on the local area in terms of requirements for new ports, roads, airports, or schools. This category of costs is referred to as infrastructure impacts. Because of the control exercised by local governments over development in the coastal zone, and given their ability to pass on the extraordinary costs of new development of this kind through impact fees, special assessments, requirements for provision of roads and sewer systems

and the like, it is unlikely that any seriously conflicting onshore development would be permitted in the study area or that the costs of required new infrastructure would be paid by existing taxpayers. The net fiscal impact of new industrial development in local areas is generally believed to be neutral or positive, as is evidenced in the fact that many local governments in Florida have sought to attract new industries expecting to recover for any short-run costs through expansion of their tax base. After reviewing several studies of the benefits and costs to local governments of OCS oil development, the MMS concluded that the most reasonable hypothesis is that such development has no net fiscal impact (MMS 1987b, p. G-53).

A study of the actual demands on a local economy in Florida resulting from the drilling of a well in the East Bay area near Pensacola concluded that about two-thirds of the workers and field service companies involved in the drilling program came from locations outside of Florida (Herbert and Lampl 1983).

In 1987, the MMS estimated that infrastructure requirements for developing leases in the entire Eastern Gulf of Mexico Planning Area would include 2 platforms, 19 exploration wells, 36 development and production wells, and 1 new support base (MMS 1987b, Appendix K). All of the other facilities, including pipelines and processing facilities, are already in place in the central Gulf of Mexico region. Only 400 new jobs and a population increase in Florida of 300 are expected to result from this development plan (MMS 1987b). Leasing in the Straits of Florida Planning Area was projected to result in 1 platform, 9 exploration wells, 13 development and production wells, and 1 gas pipeline to shore. The initial supply base for drilling in the Eastern Gulf of Mexico Planning Area would probably be Port Manatee (outside of the study area), which should already have sufficient capacity to accommodate the new activity (Martin 1989; Schanck 1989). An unlikely (marginally suitable) temporary supply base could also be created in Ft. Myers (see **Chapter 12**). Because of the limited amount of new construction that would be required and the location outside of the study area of major onshore facilities such as supply bases, gas processing plants, and refineries, there will be little demand on local governments in the study area to provide new infrastructure. Thus the conclusion that the proposed OCS leases will have no net fiscal impact on local governments in the study area appears to be warranted.

SUMMARY OF ESTIMATED ECONOMIC EFFECTS

Economists providing economic impact analysis to the MMS have studied many important aspects of the national and regional damage costs which might be expected in the event of an oil spill resulting from OCS lease development in 22 OCS Planning Areas, including the Eastern Gulf of Mexico and the Straits of Florida (MMS 1987b, Appendix G). They have converted "costs per oil spill incident" estimates from studies of previous oil spill cases to a "cost per barrel of oil spilled," which they have then applied to each Planning Area on the basis of its individual ecological characteristics and other factors. The results of that analysis for the study area are summarized in **Table 16.1.**[9]

[9]A separate study conducted for the MMS has developed a regional input-output model to assess the local area impact of OCS oil and gas activities in the Gulf of Mexico on population, the distribution of employment among various industries, and regional income (Lamphear et al. 1986). This model was developed to focus on areas with highly developed oil production and related infrastructure; thus, the model's estimates of impacts are most relevant to Louisiana and Texas.

Table 16.1. Cost per barrel of oil spilled, Eastern Gulf of Mexico and Straits of Florida Planning Areas (From: Minerals Management Service 1987b, Appendix G).

Type of Cost	Cost (1987 dollars)
Environmental costs	106-182
Recreation and tourism costs (oil hits shore)	673
Costs to local economy (tourism losses)	484
Costs to commercial fisheries (including secondary losses)	42-64
Cleanup and control (platform spill)	
Oil hits shore	225
Oil remains at sea	102
Air quality impairment	negligible
Impacts on property values	46
Water quality impairment	negligible
Infrastructure costs	negligible
Legal-administrative costs	18
Research costs	8

Based on the estimates reported in **Table 16.1**, the total costs of an oil spill in the study area (including costs to the local economy) are estimated to be $1,602 to $1,700 per barrel of oil reaching shore plus $276 to $374 per barrel spilled but not reaching shore.[10]

The MMS has estimated a 10% probability of one or more oil spills $\geq$1,000 barrels occurring over the 35-year life of the proposed leases in the study area (MMS 1987a, IV.B.6.-5). The MMS conducted extensive analyses of spill probabilities in the Eastern Gulf of Mexico and Straits of Florida Planning Areas (using the mid-1987 estimates of total economically recoverable resources in these two Planning Areas and assuming development and production of these resources over a 35-year time period) and concluded that the expected total amount of oil spilled at a crude oil price of $29 per barrel (1987 dollars) would be 9,533 barrels reaching shore plus 10,999 barrels remaining at sea (MMS 1987b, p. G-63).

No resource estimates have been made for the study area alone, which encompasses portions of the Eastern Gulf of Mexico and Straits of Florida Planning Areas. The most recent risked mean estimate of economically recoverable oil in the Straits of Florida Planning Area is 63 million barrels of oil (U.S. Geological Survey [USGS] and MMS 1989). The most recent estimate for the leased and unleased portions of the Eastern Gulf of Mexico Planning Area south of 26°N (excluding the study area) is 610 million barrels of oil (MMS 1989a). Assuming on the basis of the relative acreage involved that the portion of the study area within the Eastern Gulf of Mexico Planning Area contains about one-third as much crude oil as estimated above for the region south of 26°N, the total resource base in the study area would include 266 million barrels of economically recoverable crude oil, or about 1.06 times the estimate used in the 1987 MMS spill projection cited above. Multiplying the spillage figures given above by 1.06 yields estimates of oil spillage in the study area, over the 35-year life of the proposed leases, of 10,105 barrels of oil reaching shore and 11,659 barrels remaining at sea.

[10]Analysts involved in making the MMS estimates have also developed an ocean systems/economic model to predict damages to marine resources under the Comprehensive Environmental Compensation and Liability Act (CERCLA). The latter damages do not include all the loss categories listed in the MMS analysis, but the model could be applied to important categories of loss such as public beaches and commercial fisheries (Grigalunas et al. 1988).

Assuming for the sake of simplicity that the costs per barrel of oil spills will rise after 1987 at the same rate as the discount rate, the cost estimates reported in **Table 16.1** are equivalent to the present discounted value (in 1987) of the costs of an oil spill in any future year. Using this simplifying assumption, we may multiply the estimated total costs per barrel from **Table 16.1** (using the mid-points of the estimated ranges) by the expected total quantity of oil spilled (as explained in the paragraph above) to obtain a total expected cost. For the study area alone, the expected cost (in 1987 dollars) following this approach amounts to $20.5 million.

An alternative estimate using the costs reported in **Table 16.1** may be based on a hypothetical spill equal in size to that which occurred in Santa Barbara (77,000 barrels). Assuming that as much as one-half the oil spilled in an incident of this magnitude reached the shore, the estimated costs of the spill would be $76 million (1987 dollars).[11]

The value to society of developing the unleased resources in the study area will depend upon the amounts of oil and gas actually discovered, and this cannot be known in advance of drilling. However, assuming (1) that the USGS and MMS (1989) resource estimates for the Straits of Florida Planning Area are correct; (2) that the MMS (1989a) resource estimates for the Eastern Gulf of Mexico Planning Area south of 26° N are correct; and (3) that the portion of the Eastern Gulf of Mexico Planning Area within the current study area contains about one-third as much oil and gas as the region south of 26° N covered by the MMS (1989a) estimates, then the total amount of economically recoverable resources within the study area can be estimated at 266 million barrels of crude oil and 105.7 billion cubic feet of natural gas.

These resources would be produced in future years, but assuming the net benefits to society of increased production from the OCS rise each year at the same rate as the discount rate, the estimates developed above for the net social benefits of incremental production from the OCS ($17 per barrel of oil) may be used as an estimate of their present value. Following this approach, it may be concluded that these benefits amount to $4.5 billion (present value). It should be noted again that this estimate is probably conservative since it ignores the additional benefits to society that would be provided by the production of natural gas from the study area.

On the assumption that Florida will receive only a 5% share of the net benefits of leasing (its share of the U.S. population), but will incur all of the costs of leasing which were estimated above, the net benefits to Florida would still be quite large ($225 million in expected benefits and $20.5 million to $76 million in expected costs). Of course, Florida would not bear all of the costs of an OCS oil spill. Using the experience of previous spills as a guide, a majority of the costs would be paid by the oil companies responsible for the spill (or their insurers). A large share of the remaining costs would be paid by the Federal government or through the operation of compensation funds.

To the degree that the actual volume of resources discovered offshore Florida was smaller than estimated in the MMS analysis, so also would the projected total amount of oil spilled over the period of development be smaller. The benefits to society would decline, but at the same time the potential costs to society (and to Florida in particular) would also decline in a roughly proportional manner.

[11] A spill as large as that which occurred in Santa Barbara is highly unlikely for the reasons given earlier (footnote 6), but the costs per barrel of oil spilled offshore Florida could also be higher. The *Exxon Valdez* oil spill was not OCS-related and also occurred in a particularly hostile and high-cost environment. It is worth noting, nevertheless, that this spill has already cost about $8,000 per barrel of oil spilled (or more than eight times the cost per barrel of the Santa Barbara spill).

The analytical approach followed here has many inherent difficulties, since it is based on studies of oil spills in other areas with different relative impact costs. Although all the oil spill costs used in the analysis have been updated to account for inflation (to 1987 price levels), concerns may be raised that an actual oil spill offshore Florida in a future year would require greater efforts in cleanup and control (and higher relative costs) than were experienced in earlier time periods and other places, or that some categories of cost (such as damage to coral reefs and seagrasses or to specialized forms of recreation such as sport fishing and reef diving) may be greater in the case of Florida than what has been experienced in other areas.

The cost estimates presented here also include no allowance for social effects of the type described in the NRC (1989) report, nor do they include newer categories of economic damages such as "preservation" or "existence" values, assuming these types of damages are ultimately accepted in law and economics.

CONCLUSIONS

The economic effects of OCS oil and gas development in the study area (discussed above) have been based on hypotheses concerning the estimated volume of resources which may be recovered in the study area, the number and location of wells drilled and platforms constructed to produce these resources, and the type and location of the transportation and service facilities needed to bring any produced resources to market. These hypotheses cannot be verified until the leases are sold, exploratory drilling is completed, and plans for production are finalized. Thus, important information needed to conduct an accurate assessment of socioeconomic effects cannot be known in advance of drilling.

In view of this difficulty, it has been suggested that OCS leasing be carried out in two stages. Permission to proceed with development would be granted only after exploratory drilling discovered sufficient resources in place and after environmental and socioeconomic analyses were conducted on the basis of the development plan submitted for recovering these resources.

This two-stage procedure raises serious new problems, however, including a reduction in the size of the bonus bids that companies would be willing to pay for the right to carry out exploratory drilling programs, probable future cost-sharing by the public of some exploratory drilling costs, and the creation of additional legal and regulatory barriers to ultimate development and production. In view of these problems, it is apparent that a two-stage leasing system would not necessarily improve the overall efficiency of the OCS leasing program of the Nation. It is likely, therefore, that OCS leasing decisions will continue to be made in the face of limited information concerning specific development plans for the lease sale area.

This chapter has relied on the experience of OCS leasing in other areas to develop a set of benefit and cost estimates which were then applied to the study area. These estimates indicate that OCS leasing in the study area would probably yield large net economic benefits to the U.S. public generally and smaller but still positive net benefits to Florida also, assuming the absence of major changes in future environmental costs or other features of the model used.

This conclusion must be tempered by two caveats: (1) no study has been completed of the sociological effects of OCS leasing in the study area; and (2) a potentially important category of economic costs has not been included in the cost estimates used in the analysis presented in this chapter. While additional refinements of the cost estimates given in this chapter will be provided in a new study of the costs of OCS

development (to be included in the 5-Year Program for 1992 to 1997), this research will not fill the gaps in information noted above.

Sociological studies of the possible effects of OCS leasing in a community such as Key West in the heart of the study area would answer at least some of the questions raised in the NRC (1989) report cited earlier and would possibly also permit a policy evaluation to be made concerning the validity and usefulness of this type of impact analysis.

Economic studies of the user and non-user damages which would be sustained in the event of a degradation of the coral reefs (or other special environments) in the study area as a result of routine oil and gas operations or a significant oil spill--a category of costs for which little or no information currently exists--should also be a high priority for future MMS research. Questions concerning the importance of the "existence," "preservation," and "option" values of these important environmental assets will continue to be raised. Since this category of potential damages incorporates a large part of the general public's concern over OCS leasing, it would seem appropriate that research studies be carried out in this area despite the reservations that will continue to be raised concerning the meaning and validity of these categories of damages.

Finally, additional research efforts should be focused on tourist and resident recreation patterns in the study area, with a particular emphasis on the user-value (or consumer's surplus) yielded by such activities as beach visits, swimming at the beach, and saltwater fishing. This research could be conducted at small additional cost if it were carried out as part of the existing tourist survey of the Florida Department of Commerce. Additional data for residents could then be provided by means of a Statewide survey of the type routinely conducted by the Policy Sciences Program at Florida State University (or any similar Statewide survey).

REFERENCES CITED

Adams, C. 1987. *An economic perspective on Florida's changing marine water dependency*. Food and Resource Department Staff Paper No. 303. Gainesville: Univ. of Florida.

American Petroleum Institute. 1984. *Should offshore oil be put off limits?* Washington, DC.

American Petroleum Institute. 1989. *The American Petroleum Institute task force report on oil spills*. Washington, DC.

Bell, F. 1989. *Application of wetland valuation theory to commercial and recreational fisheries in Florida*. Florida Sea Grant Program Rep. No. 95. Gainesville: Univ. of Florida.

Bell, F., and R. Leeworthy. 1986. *An economic analysis of saltwater beaches in Florida*. Florida Sea Grant Program Rep. No. 82. Gainesville: Univ. of Florida.

Bell, F., P. Sorensen, and R. Leeworthy. 1982. *The economic impact and valuation of saltwater recreational fisheries in Florida*. Florida Sea Grant Program Rep. No. 47. Gainesville: Univ. of Florida.

Brown, G. M., Jr. 1983. Noncommercial marine biomass and seabirds. In *Assessing the social costs of oil spills: The Amoco Cadiz case study*, 81-85. Washington, DC: U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Brown, G. M., Jr., R. Congar, and E. Wilman. 1983. Recreation: Tourists and residents. In *Assessing the social costs of oil spills: The Amoco Cadiz case study*, 89-108. Washington, DC: U.S. Department of Commerce, National Oceanic and Atmospheric Administration.

Cato, J. C. 1989. Statement to the Presidential outer continental shelf leasing and development task force, 15 June 1989, Miami, FL.

Centaur Associates, Inc. 1981. *Assessment of space and use conflicts between the fishing and oil industries*. Washington, DC: U.S. Department of the Interior, Bureau of Land Management.

David Dornbusch and Co. 1987. *Impacts of outer continental shelf (OCS) development on recreation and tourism*. Los Angeles: U.S. Department of the Interior, Minerals Management Service.

Desvousges, W., and V. Skahen. 1985. *Measuring natural resource damages: An economic perspective*. U.S. Environmental Protection Agency Rep. No. 68-01-7033. Raleigh: Research Triangle Institute.

Energy Information Administration. 1989. *Monthly energy review*. DOE/EIA-0035 (89/03). Washington, DC: U.S. Government Printing Office.

Engelhardt, F. R., J. P. Ray, and A. H. Gillam, ed. 1989. *Drilling wastes. Proceedings of the 1988 International Conference on Drilling Wastes*. London: Elsevier Applied Science Publishers Ltd.

Freeman, R., S. Holland, and R. Ditton. 1985. Measuring the impact of the *Ixtoc I* oil spill on visitation at three Texas public coastal parks. Unpubl. manuscript.

Gaines, T. H. 1969. Oil pollution control--Santa Barbara. Paper presented at 40th Annual Meeting of the Society of Petroleum Engineers, 6-7 November 1969, San Francisco, CA.

Griffin, J., and H. Steele. 1986. *Energy economics and policy*, 2nd edition. Orlando: Academic Press.

Grigalunas, T. A. et al. 1988. Measuring damages to marine natural resources from pollution incidents under CERCLA: Applications of an integrated ocean systems/economic model. *Mar. Resour. Econ.* 5:1-21.
Herbert, T. A., and L. Lampl. 1983. *The travel and residency patterns of rig workers: The Getty Oil Company East Bay project.* Unpubl. research report. Tallahassee.
Jackson, J. B. C., J. D. Cubit, B. D. Keller, V. Batista, K. A. Burns, H. M. Caffey, R. L. Caldwell, S. D. Garrity, C. D. Getter, C. Gonzalez, H. M. Guzman, K. W. Kaufmann, A. H. Knap, S. C. Levings, M. J. Marshall, R. Steger, R. C. Thompson, and E. Weil. 1989. Ecological effects of a major oil spill on Panamanian coastal marine communities. *Science* 243:37-44.
Lamphear, F. C. et al. 1986. *Analysis of indicators for socioeconomic impacts due to OCS oil and gas activities in the Gulf of Mexico, year II.* New Orleans: U.S. Department of the Interior, Minerals Management Service.
Martin, J. C. 1989. Oil spill contingency plans. Statement to the Presidential outer continental shelf leasing and development task force, 16 June 1989, Key West, FL.
Martinez, B. 1989. Governor's statement to the Presidential outer continental shelf leasing and development task force, 12 June 1989, Tallahassee, FL.
Mead, W. J., and P. E. Sorensen. 1970. The economic cost of the Santa Barbara oil spill. In *Santa Barbara oil symposium.* Santa Barbara: Mar. Sci. Inst., Univ. of California.
Mead, W. J. et al. 1986. *Offshore lands: Oil and gas leasing and conservation on the outer continental shelf.* San Francisco: Pacific Institute for Public Policy Research.
Milon, W., and C. Adams. 1987. *The economic impact of Florida's recreational boating industry in 1985.* Florida Sea Grant Tech. Pap. No. 50. Gainesville, FL.
Minerals Management Service. 1983. *From policy to production: Offshore leasing and operations.* Washington, DC: U.S. Government Printing Office.
Minerals Management Service. 1986. *Federal offshore statistics: 1984.* OCS Rep. MMS 86-0067. Washington, DC: U.S. Government Printing Office.
Minerals Management Service. 1987a. *Proposed 5-year outer continental shelf oil and gas leasing program, mid-1987 to mid-1992. Final environmental impact statement.* OCS EIS-EA MMS 86-0127. Washington, DC: U.S. Government Printing Office.
Minerals Management Service. 1987b. *5-year leasing program, mid-1987 to mid-1992. Detailed decision documents.* Washington, DC: U.S. Government Printing Office.
Minerals Management Service. 1989a. *Mid-price scenario, estimates of undiscovered economically recoverable oil and gas resources as of July 1989, eastern Gulf of Mexico region, Table 1.* Document dated 21 September 1989.
Minerals Management Service. 1989b. *Federal offshore statistics: 1988.* OCS Rep. MMS 89-0082. Herndon, VA: U.S. Department of the Interior, Minerals Management Service.
National Research Council. 1983. *Drilling discharges in the marine environment.* Washington, DC: National Academy Press.
National Research Council. 1989. *The adequacy of environmental information for outer continental shelf oil and gas decisions: Florida and California.* Washington, DC: National Academy Press.
Oil and Gas Journal. 1989. *U.S. industry draws up oil spill response plan.* 26 June, p. 18.
Petroleum Industry Response Organization Steering Committee. 1990. *Steering committee report and recommendations on the implementation of PIRO.* Washington, DC.
Plummer, J. 1981. Methods for measuring the oil import reduction premium and the oil stockpile premium. *The Energy J.* 2:1-18.
Restrepo, C. E., F. C. Lamphear, C. A. Gunn, R. B. Ditton, J. D. Nichols, and L. S. Restrepo. 1982. *Ixtoc I oil spill economic impact.* New Orleans: U.S. Department of the Interior, Bureau of Land Management. NTIS Nos. PB82-217860, PB82-217852, and PB82-217878.
Royal Commission on Environmental Pollution. 1981. *Oil pollution of the sea, Eighth report.* London.
Schanck, J. W. 1989. Statement to the Presidential outer continental shelf leasing and development task force, 13 June 1989, Ft. Myers, FL.
Sorensen, P. E. 1975. *Estimated loss of catch resulting from the Santa Barbara oil spill.* Report prepared for the U.S. District Court, Los Angeles.
Sorensen, P. E. 1977. *Summary of damages to the Commonwealth of Puerto Rico caused by the Bahia Sucia oil spill of March 1973.* Report prepared for the U.S. District Court, Puerto Rico.
Sorensen, P. E. 1983. Marine resources. In *Assessing the social costs of oil spills: The Amoco Cadiz case study,* 57-87. Washington, DC: U.S. Department of Commerce, National Oceanic and Atmospheric Administration.
South Florida Regional Planning Council. 1984. *OCS facility siting study.* Hollywood, FL.
Twachtmann, D. 1989. Statement by the Secretary of the Department of Environmental Regulation to the Presidential outer continental shelf leasing and development task force, 12 June 1989, Tallahassee, FL.
U.S. Geological Survey and Minerals Management Service. 1989. *Estimates of undiscovered conventional oil and gas resources in the United States--A part of the Nation's energy endowment.* Washington, DC: U.S. Government Printing Office.
Wilman, E. A. 1984. *External costs of coastal beach pollution, an hedonic approach.* Washington, DC: Resources for the Future.

CHAPTER 17
CONCLUSIONS AND RECOMMENDATIONS

Neal W. Phillips

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INTRODUCTION

This report had three main goals: (1) to review and synthesize geological, chemical, biological, cultural resource, and socioeconomic information for the study area (**Figure 17.1**); (2) to evaluate potential effects of offshore oil and gas operations; and (3) to recommend mitigation measures and evaluate future research needs.

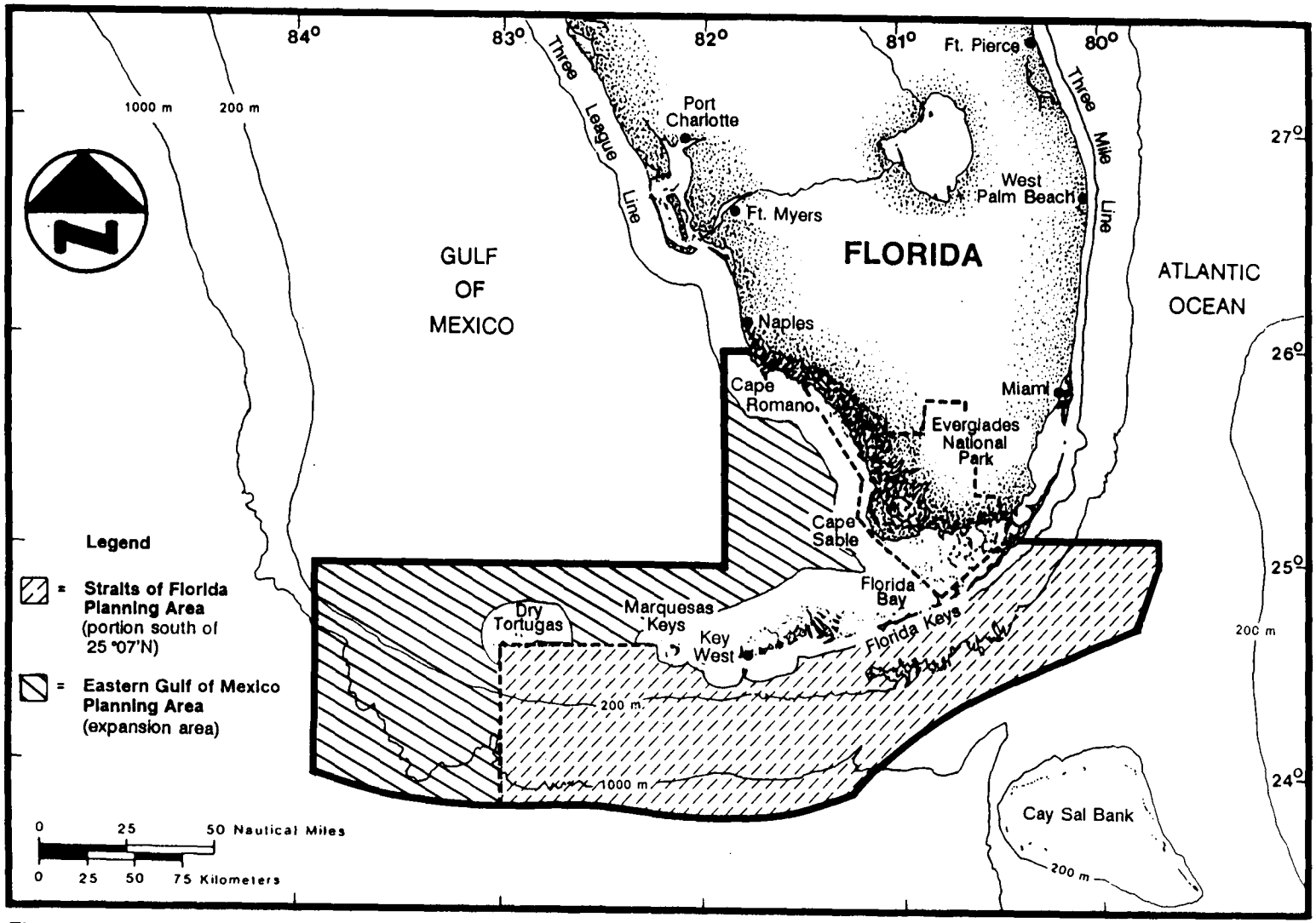

Figure 17.1. Study area.

All of these topics have been discussed in the preceding chapters. However, in **Chapters 2** through **11**, the main focus was on basic knowledge, rather than information needed for decisions about outer continental shelf (OCS) oil and gas operations. In **Chapters 12** through **16**, the main focus was potential effects of OCS activities. The purpose of this chapter is to draw together information from the various chapters, highlighting significant findings and information needs in the context of OCS decision-making.

In preparing this chapter, I have selectively drawn information (and in some cases, text) from the other chapters. The conclusions and recommendations presented here are based on my interpretation of the data and do not necessarily reflect the views of the other chapter authors.

The first part of the chapter focuses on conclusions concerning the South Florida environment. Characteristics that should be taken into account in decisions about offshore leasing are highlighted--especially those relating to the sensitivity of the environment to oil spills and other agents of change. The second part focuses on conclusions about oil and gas operations, including resource potential, level of exploration and development activity, and environmental and socioeconomic effects. The third section evaluates information needs identified by chapter authors in relation to decisions about oil and gas leasing. A final section recommends mitigation measures and further studies.

CONCLUSIONS CONCERNING THE SOUTH FLORIDA ENVIRONMENT

Physical/Chemical Environment

Climate is an important influence on South Florida's marine communities. In particular, the Florida Reef Tract is near the northern limit of active reef development. Temperatures are sufficiently mild most of the time to support reef-building corals and other Caribbean flora and fauna. However, occasional winter cold fronts can kill or injure corals, reef fishes, and other tropical biota. Conversely, prolonged high temperatures during late summer doldrums produce massive coral bleaching events once or twice a decade. Hurricanes can kill, damage, or stress reef corals, mangroves, seagrasses, and associated fauna. The effects of oil and gas operations on coastal and nearshore communities must be evaluated in the context of these natural stresses (and others brought on by activities of an expanding human population) that may limit the ability of these communities to recover from environmental damage.

The geographic configuration of the study area is also important for several reasons. The Florida Keys archipelago divides the study area into geologically and oceanographically distinct subregions (**Chapter 2**). Key Largo and the Lower Keys shield portions of the Florida Reef Tract from cold water outflows from Florida Bay during winter, allowing reef-building corals to thrive (**Chapter 4**). Due to the presence of the Florida Keys, the Ten Thousand Islands, and the many mangrove islands in Florida Bay, there is more shoreline per unit of leasable acreage in the study area than in any other OCS Planning Area outside Alaska. Much of this shoreline consists of low-energy habitats such as sheltered mangrove forests and tidal flats, where spilled oil would persist and cleanup would be difficult or impossible (**Chapter 15**). In some areas, such as the Ten Thousand Islands and the Lower Keys, the complex network of islands and channels would make the logistics of oil spill response very difficult. The basin-in-basin "honeycomb" topography of Florida Bay is also important because seagrass communities thrive atop shallow mudbanks separating the basins. Because of the shallow water depth (some mudbanks are partly exposed at low tide), the associated seagrass communities would be very susceptible to oiling (**Chapter 4**). Shallow water would also severely limit oil spill response and cleanup measures in Florida Bay.

Though not a topic of this report, physical oceanography is a major consideration in the study area. The Loop Current and the Florida Current affect sediment distribution (**Chapter 2**), transport larvae of fish and invertebrates (**Chapter 6**), and carry pelagic tar from the Gulf of Mexico around to Southeast Florida beaches (**Chapter 3**). Loop Current intrusions stimulate water column primary productivity over the Southwest Florida shelf (**Chapter 6**), potentially releasing pulses of organic matter to the benthos. Geostrophic upwelling due to passage of the Loop Current along the edge of the Southwest Florida shelf results in high near-bottom nutrient levels on the middle shelf, which may contribute to the predominance of dense algal live bottom communities there (**Chapter 5**). The restricted circulation of Florida Bay affects the geological, hydrographic, and biological characteristics of the bay. The Florida Current influences the routes of oil tankers through the Straits of Florida: those traveling east and north through the Straits stay well offshore to ride the current, whereas those going the other way travel closer to shore to avoid the strong flow (**Chapter 12**).

Because of the area's low overall population density, low level of industrial development, predominantly carbonate sediments, and lack of major rivers, concentrations of chemical contaminants are generally low (**Chapter 3**). Local elevations in trace metal concentrations may occur near power plants, boat basins, and other sites of human activity. Moderate to high concentrations of pelagic tar occur in the Straits of Florida, and these originate mainly from crude oil discharges by tankers in the Gulf of Mexico.

South Florida's trace metal and hydrocarbon characteristics illustrate a major difference between the study area and the northwestern Gulf of Mexico, where most previous offshore drilling and production have occurred. In the northwestern Gulf, the Mississippi and Atchafalaya Rivers transport huge volumes of water and sediment to the ocean. The quantities of sediment, trace metals, and hydrocarbons from this source can mask local changes in the environment caused by offshore oil and gas operations. Moreover, the environmental variability caused by the Mississippi River outflow has profound effects on benthic and pelagic ecosystems, sometimes making it difficult to detect biological effects of oil and gas operations. In contrast, additions of trace metals and petroleum hydrocarbons from oil and gas operations in South Florida should be readily detectable. The isolation of South Florida from the Mississippi River influence removes one major source of environmental variability, perhaps making it easier to detect changes in some biological communities.

Water quality problems have been identified with the urbanization of South Florida and will continue to require research and management, regardless of whether offshore leasing occurs. The problems include turbidity from dredge and fill projects, hypersalinity due to evaporation and limited freshwater discharge into Florida Bay, introduction of pesticides from agricultural drainage, and nutrient enrichment of groundwater and nearshore waters due to onsite sewage disposal in the Florida Keys. These problems are all part of the context in which any new human activity such as offshore drilling must be evaluated.

Biota

Coastal and Nearshore Communities

The combination of mangrove forests, coral reefs, and seagrass beds found in the study area does not occur anywhere else in the U.S. On the basis of its natural beauty and its ecological and economic importance, this interrelated system can be considered a State and National treasure. South Florida's valuable commercial and recreational fisheries depend on numerous species that inhabit mangrove forests, coral reefs, or seagrass beds during all or parts of their life cycles (**Chapters 4 and 7**). These

ecosystems provide habitat and/or foraging grounds for many species of coastal and marine birds (**Chapter 9**). In addition, South Florida's coral reefs serve as natural breakwaters and provide an array of recreational opportunities that attracts millions of tourists each year (**Chapter 11**).

The State and the Nation place a great deal of importance on preservation of South Florida's coastal and nearshore habitats. The study area includes 60 sites of special concern, including State and National parks, aquatic preserves, wildlife refuges, and marine and estuarine sanctuaries. Prominent among these are Everglades National Park, Fort Jefferson National Monument, and the Key Largo and Looe Key National Marine Sanctuaries. In addition, the entire Florida Keys has been designated by the State as Outstanding Florida Waters and as an Area of Critical State Concern. The Everglades has been designated by the United Nations as an International Biosphere Reserve and a World Heritage Site.

South Florida's coastal and nearshore communities are subject to damage and stress by natural events such as hurricanes and cold fronts, as well as human activities associated with development in the Florida Keys (**Chapter 4**). The Florida Reef Tract exists at the northern threshold for reef development, and it is threatened by sediment influx and nutrient enrichment resulting from coastal development. Because of the existing threats and the decline in reef vitality in recent years, the ability of the reefs to recover from major environmental damage is uncertain. Most mangroves within the study area grow under less-than-optimum conditions and can be classified as stressed. Coastal urbanization threatens seagrass and coral reef habitats by removing terrestrial vegetation and mangroves, which act as filters that absorb nutrient- and sediment-laden runoff. Occasional freshwater releases from canals into Florida Bay can result in severe damage to seagrass communities. Recent events such as the massive seagrass die-off in Florida Bay and coral bleaching in the Reef Tract illustrate the fact that the continued health of these communities cannot be taken for granted. Any new human activity that might affect these communities must be evaluated against this background.

Offshore Benthic Communities

Hard bottom communities and deepwater seagrass meadows occur widely in Federal waters of the Southwest Florida shelf and on the shelf offshore of the Florida Reef Tract (**Chapter 5**). Although much information about the distribution of benthic communities is available through recent Minerals Management Service (MMS) studies, little is known about the ecological importance of these communities or their sensitivity to physical disturbance, sediment deposition, and chemical contamination.

Hard bottom areas and deepwater seagrass meadows are accorded special consideration by the MMS and the State of Florida. This regulatory protection is based on a simplistic view of these areas as "oases" of productivity in a "desert" of sand bottom (**Chapter 5**). Soft bottom areas (which serve as foraging grounds for many hard bottom fishes) and macroalgal communities are not accorded special protection. Whatever the merits of the regulatory scheme, the presence of hard bottom communities and deepwater seagrass meadows is certain to influence the course of OCS development in the study area. Because these communities are so widely distributed, every stage of OCS operations is likely to be complicated by the need for additional studies and protective measures.

Plankton

Subtropical and tropical, oligotrophic waters such as those of the study area have tightly coupled pelagic food webs (**Chapter 6**). Steady-state phytoplankton biomass and productivity are maintained by zooplankton grazing and nutrient excretion. Therefore, these ecosystems may be extremely vulnerable to perturbations at lower trophic levels. Nearshore and estuarine zooplankton populations may be more sensitive than open ocean populations to surface contaminants because restricted circulation limits reinoculation with new recruits. Meroplankton, particularly the larvae of commercially important fish species, are more abundant in nearshore and estuarine waters, where they are especially vulnerable to oiling.

Fish Communities and Fisheries Biology

South Florida possesses a diverse fish fauna, including many species of commercial or recreational importance (**Chapter 7**). (The economic importance of area fisheries is discussed below under Socioeconomics). The diversity of fishery resources within the study area is unparalleled in the continental U.S. At one life stage or another, many species of fish and shellfish, including pink shrimp, spiny lobster, and stone crab, inhabit coastal and nearshore ecosystems such as mangrove forests, coral reefs, and seagrass beds. Area fisheries are therefore dependent on the continued health of these ecosystems.

Most species of commercially and recreationally valuable fish have pelagic eggs that undergo initial development in surface waters (as ichthyoplankton), where they would be susceptible to oil. Because of the restricted nature of seasonal spawning and the concentration of eggs and larvae over spawning grounds and nursery areas, nearshore and estuarine fish populations could be very susceptible to damage by oil reaching coastal waters.

Several fishery species in South Florida, both migratory and resident species, are overexploited (**Chapter 7**). Any additional source of mortality from human activities is of concern.

Two protected fish species are found only in the Lower Keys: the Key silverside (*Menidia conchorum*) and the Key blenny (*Starksia starcki*) (**Chapter 15**). Both species are year-round residents. The Key silverside is a Florida Threatened species, and the Key blenny is a Florida Species of Special Concern. Because these species live only in shallow, coastal waters of the Lower Keys, a large oil spill could affect the entire population of either species.

Marine Mammals and Sea Turtles

Thirty species of marine mammals and five species of sea turtles may be found in the study area (**Chapter 8**). Six of the marine mammal species (five whales and the Florida manatee) are Endangered. Four of the sea turtles (green, hawksbill, Kemp's ridley, and leatherback) are Endangered, and one (loggerhead) is Threatened. The Florida manatee and the bottlenose dolphin are the most common marine mammals in the study area. All of the sea turtles occur in the study area, but only the loggerhead nests there.

Potential sources of mortality to any Endangered or Threatened species (as well as to any marine mammal, under the Marine Mammal Protection Act) should be cause for concern. Two species are of particular concern with regard to oil spills, as indicated below:

- **Florida manatee**. This Endangered species is increasingly threatened by human activities in the coastal environment, especially boat traffic. Because of the species' low population size (about 1,200 individuals in Florida), low reproductive rate, and high yearly death rate (about 120 animals), any potential source of additional mortality is of great concern. Manatees are found in coastal waters throughout the study area, and they tend to congregate during winter, when they presumably would be most vulnerable to an oil spill.

- **Loggerhead sea turtle**. This Threatened species nests on the beaches of Southwest Florida, the Florida Keys, and the Dry Tortugas. Thus, loggerheads would be more vulnerable than the other sea turtles to consequences of an oil spill, such as contamination of nesting areas and physical/mechanical damage to nests during cleanup activities. Other human activities, such as habitat destruction (nesting beaches, seagrass beds), incidental take in fisheries (drift gillnets, purse seines, long-lines, shrimp trawls), entanglement in and ingestion of plastic debris, etc. are killing these animals in increasing numbers.

Coastal and Marine Birds

South Florida's extensive wetlands and other coastal habitats serve as nesting and feeding grounds for over 100 species of coastal and marine birds (**Chapter 9**). In addition to the year-round inhabitants, many birds are seasonal residents or pass through the area during migrations. The variety of bird life supports popular recreational activity such as birdwatching and hunting, and it is a major element in the aesthetic appeal of South Florida to tourists and residents.

South Florida's avifauna includes populations of 27 protected species (**Chapter 9**). One reason for the large number of Endangered and Threatened species is the widespread destruction and alteration of South Florida native habitats due to human development. Human-altered water flow patterns in the Everglades are responsible for the decline of some species (e.g., the Wood Stork).

Many South Florida bird species nest, forage, or breed in coastal wetlands or on islands, where they would be extremely vulnerable to oiling. Many species are dependent on the continued health of mangrove communities. Several unique bird populations in the study area could be jeopardized by a single catastrophic event such as a large oil spill. Some examples are listed below (see **Chapter 9** for more information).

- **Great Blue Heron (white color morph)**. The major range and virtually the entire nesting area of the white color morph lies within the study area (Florida Bay and the Lower Keys). The population, estimated at about 900 birds, is largely sedentary. Recent studies indicate a lack of reproductive success of this color morph, apparently due to inadequate food supplies.

- **Reddish Egret**. The Florida Bay population of this Florida Species of Special Concern is probably a unique one in terms of its gene pool, and the population is estimated at below 300 pairs. The Reddish Egret is a sedentary species that has become ecologically restricted to an area where the productivity of its food sources has become marginal.

- Roseate Spoonbill. The Roseate Spoonbill is a Florida Species of Special Concern. The species recovered from near extinction earlier in the century, but the population is once again stressed and in decline because of inadequate food supplies due to altered freshwater flow from the Everglades. The spoonbills in Florida Bay constitute a distinct subpopulation that has developed "traditions" to this area (e.g., when and where to migrate and nest). This means that if the subpopulation were destroyed, the area would not soon be colonized by new individuals from other areas.

- Roseate Tern. The South Florida population of this Threatened species is the only one in the U.S. south of North Carolina. A colony of about 300 breeding pairs on a freshly bulldozed Key West harbor island could be the largest colony in the eastern U.S.; the entire North American population is estimated at 2,500 pairs.

- Sooty Tern and Brown Noddy. Both species, though not on the Endangered or Threatened list, would be particularly vulnerable to oiling during their spring-summer nesting period at Bush Key in the Dry Tortugas. The Dry Tortugas are the only important nesting ground in the continental U.S. for both species. Sooty Terns nest from March through August, with over 80,000 individuals present. Several hundred to several thousand Brown Noddies nest there from March through October.

- Southeastern Snowy Plover. Gulf coast beaches in the Cape Romano area are one of the few remaining nesting sites of this Florida Threatened species. It is estimated that only 100 to 200 animals remain in Florida.

Because of the large number of seasonal residents and migratory visitors from all over the continent, damage to South Florida bird populations could have serious implications well beyond the study area. Of particular concern is the Dry Tortugas, known internationally for its unusually rich avifauna, especially the "ternery" where thousands of terns come to nest and rear their young each year (**Chapter 9**). Depending on season, oil reaching the Dry Tortugas could jeopardize breeding populations, wintering populations, or migrating populations of a spectrum of species with both marine and terrestrial affinities. Also, important rookeries of cormorants, pelicans, wading birds, and others are found along the Southwest Florida coast in the Ten Thousand Islands region. The network of islands and channels in this area would make oil spill response difficult or impossible (**Chapter 15**).

Submerged Cultural Resources

Evidence from Southwest Florida indicates that humans first entered the Florida peninsula about 12,000 years ago (**Chapter 10**). At that time, as a result of greatly lower sea levels attributable to the closing phases of the last period of glaciation, much of the study area now covered by the sea was dry land, and the correspondingly wider, longer peninsula was environmentally very different from present.

Intact, significant, prehistoric archeological resources are believed to exist in the study area (**Chapter 10**). It is unlikely that these resources will be found in waters deeper than 50 m. Prehistoric sites are more likely to be encountered off Southwest Florida than off the Florida Keys. The model of prehistoric settlement location presented in **Chapter 10** predicts that prehistoric archeological sites on the inner continental shelf are associated with specific topographic indicators that in most instances are readily detectable. These topographic indicators are (1) the 50-m bathymetric contour, (2) karstic features, (3) drowned stream channels, (4) drowned coastal features, and (5) outcrops of knappable lithic raw materials.

The Straits of Florida has long been an important shipping corridor. Since the time of the early Spanish explorers in the late 15th and early 16th centuries, many ships have foundered on South Florida reefs and shoals. The navigational hazards of the area are reflected in a diverse population of lost vessels (shipwrecks) representing various historical periods. Lost vessels of all periods can be found throughout the continental shelf; however, more vessels tend to be found in shallow water (e.g., <20 m). Locations of lost vessels can be predicted through the location of submerged topography. Lost vessels of the 19th and 20th centuries appear to be greater in number and seem to be better preserved than those of other centuries.

Lost vessels of prehistoric periods may also exist on the continental shelf, although none have yet been located. Because the prediction of the location of these lost vessels is extremely difficult given our current state of knowledge, operations on the shelf must be prepared for chance encounters.

Socioeconomics

South Florida is experiencing rapid population growth that places heavy demands on the social infrastructure and the natural environment (**Chapter 11**). Over the next 10 years, average population growth for the three counties adjoining the study area (Collier, Dade, and Monroe) is expected to be 50% higher than the national average. Over the same period, Collier County is expected to grow at four times the national average.

Current land use patterns in the study area reflect the unique and environmentally sensitive nature of the region. The study area contains over 60 areas of special concern, such as State and National parks, marine and estuarine sanctuaries, aquatic preserves, wildlife refuges, and historic sites (**Chapter 11**). Over 90% of the land area of Monroe County is within Everglades National Park or the Big Cypress National Preserve. The entire Florida Keys have been designated as Outstanding Florida Waters and an Area of Critical State Concern. At least 10 additional sites are now under consideration for conservation by land acquisition programs of the Federal and State governments as well as by private groups. The rapid rise in population and tourism in the area has increased pressure on available outdoor recreation sites by making it more difficult to acquire public lands for these purposes. Therefore, it is increasingly important to preserve the quality of the available public recreation sites in coastal areas.

The economy of the study area (especially Monroe County, which includes the Florida Keys) is tied closely to fishing, tourism, and retirement/residential development (**Chapter 11**). The Statewide economic impact of commercial fishing in the study area is estimated to be $220 million, while the economic impact of recreational fisheries is about $1.2 billion. This amounts to about 0.5% of Gross State Product in 1987. About 18% of all tourist visits within Florida occur in the study area. In total (including the recreational fisheries impacts noted above), this tourism generated approximately 3.5% of Gross State Product in recent years (or about $6.2 billion annually).

Issues relating to water supply have been critical in South Florida for several years (**Chapter 11**). The Florida Keys (Monroe County) have no potable water and could not supply water for OCS operations. Dade County has problems with available capacity and saltwater intrusion, making it unlikely that OCS operations could be supplied with water unless there are major, new investments in water facilities. Only within Collier County could a large new supply of water (non-potable) be developed for use in OCS activities. However, there are no ports in Collier County having the capacity to serve as an OCS supply base.

None of the ports in the study area could serve effectively as a supply base for OCS operations. Port Everglades, located north of Miami, is the most likely area for a support base for OCS operations in the Straits of Florida Planning Area. Port Everglades is already a major oil port, handling nearly 90% of the petroleum tonnage entering South Florida ports (**Chapter 11**). Port Manatee (in Tampa Bay) has been used as a temporary supply base for exploratory operations on the Southwest Florida shelf north of the study area.

CONCLUSIONS CONCERNING OFFSHORE OIL AND GAS OPERATIONS

Resource Potential

The South Florida Basin is a promising, frontier area for oil and gas exploration (**Chapter 12**). Its hydrocarbon potential is poorly known because few exploratory wells have been drilled in the geochemically mature offshore portions of the basin. The basin depocenter, which is the most favorable location for commercial hydrocarbons, is in the Gulf of Mexico off Southwest Florida, just north of the study area.

Within the study area, commercial hydrocarbons are more likely to be present in the Eastern Gulf of Mexico Planning Area than in the Straits of Florida Planning Area, because the former is closer to the basin depocenter. Specific resource estimates are not available for the portion of the Eastern Gulf of Mexico Planning Area that lies within the study area. However, MMS estimates for the adjacent portion of the Southwest Florida shelf south of 26°N range from 270 to 1,060 million barrels[1] of oil and from 0.04 to 0.16 trillion cubic feet of gas (**Chapter 12**). For the Straits of Florida Planning Area, estimates range from 180 to 680 million barrels of oil and 0.21 to 0.79 trillion cubic feet of gas. These estimates are termed conditional, because they hinge on the condition that at least one prospect contains economically recoverable hydrocarbons. That probability is estimated at 0.18 for the Straits of Florida Planning Area and >0.99 for the Eastern Gulf of Mexico Planning Area south of 26°N (**Chapter 12**).

In the context of the Nation's overall oil consumption (approximately 13 million barrels/day), MMS resource estimates for South Florida are modest. Also, in comparison with 25 other OCS Planning Areas, the Straits of Florida Planning Area ranks among the lowest in resource potential (**Chapter 12**). On the other hand, that portion of the Eastern Gulf of Mexico Planning Area south of 26°N is believed to contain over 60% of the economically recoverable oil in the entire Planning Area, which ranks among the top 10 Planning Areas. In addition, petroleum companies that want to drill in a frontier area could be hoping to discover new reserves that might be considerably greater than those estimated by the MMS (**Chapter 12**).

Level of OCS Activity

The MMS anticipates a low initial level of exploration and development activity in the study area (**Chapter 12**). For a lease sale in the Straits of Florida Planning Area, this would entail 9 exploratory wells, 13 development wells, and 1 production platform. Specific estimates for the portion of the study area within the Eastern Gulf of Mexico Planning Area are not available, but would probably be somewhat larger (assuming the resources are greater). The main problem with these estimates is that they depend on

[1]Barrels are the customary unit used by the MMS to report oil resources, as well as spill volumes (1 barrel = 42 U.S. gallons, or about 160 L). Gas volumes are customarily reported in trillions of cubic feet (1 cubic foot = 0.028 cubic meters).

the amount of oil and gas present. The accuracy of the existing resource estimates cannot be known in advance of exploratory drilling.

The MMS indicates that one new onshore support base and one pipeline landfall would be needed in the study area in connection with a Straits of Florida lease sale (**Chapter 12**). However, for several reasons, it is unlikely that any OCS support facilities would be located in the study area. First, there are few, if any, suitable sites. Second, the region already faces serious water management problems that would either make it impossible to supply water for OCS operations (Monroe County) or require construction of new facilities (Collier and Dade Counties) (**Chapter 11**). Third, because of public opposition to offshore drilling, it is unlikely that local governments would approve OCS facilities. Finally, the State of Florida has prohibited placement of OCS structures (including pipelines) in State waters south of 26°N on the Gulf coast and south of 27°N on the Atlantic coast, precluding the establishment of a pipeline landfall and gas processing plant in or near the study area (**Chapter 12**).

The most likely locations for shore bases would be outside the study area, at Port Manatee (in Tampa Bay) or the Port Everglades area (north of Miami). In either case, one would expect little or no OCS vessel traffic in coastal waters of the study area. Because of the long travel time from a distant shore base, it might be necessary to station a dedicated spill-response vessel at each rig or platform to contain minor spills (**Chapter 12**).

If oil production occurs in the study area, the oil most likely would be transferred directly to tankers for transportation to refineries on the U.S. East Coast or the northern Gulf of Mexico. Transportation by pipelines, which involves a lower risk of large oil spills, is economically infeasible in a frontier area with no onshore processing facilities; also, pipelines to shore would not be permitted in the study area, as noted above.

Effects on the Environment

Several environmental issues concerning OCS operations have been cited in previous chapters, including oil spills; routine discharges; drilling near biologically sensitive areas; vessel traffic; hazards to navigation; dumping of trash and debris; siting of onshore facilities; noise; space-use conflicts with trawl fisheries; and air emissions. This is not an exhaustive list, and only the first two topics (oil spills and routine discharges) have been discussed at length (in **Chapters 12, 13, 14, and 15**).

All environmental issues will need to be evaluated in detail if a lease sale proposal is developed that includes all or part of the study area. The discussion here focuses on two questions:

- Which are the most significant potential effects?
- What steps could be taken to avoid, limit, or minimize those effects?

Conceptually, environmental effects of OCS operations can be divided into those resulting from routine operations and those resulting from accidents. The main effects of routine operations are likely to be local alterations in benthic communities around drilling rigs and platforms. Because some of these communities are especially rare, valuable, and/or sensitive to disturbance, protective measures to avoid, limit, or minimize environmental damage may be needed. In contrast, an accidental oil spill could have far-reaching effects on a spectrum of organisms and ecosystems, and there are no foolproof protective measures. The greatest concern is that a spill within the study area

could quickly reach coastal waters, producing widespread damage to South Florida mangrove forests, coral reefs, and seagrass beds, as well as fish and shellfish species, marine mammals (e.g., manatees), sea turtles, and birds.

Routine Operations

Effects. Environmental effects of most routine OCS operations are localized--e.g., within particular lease blocks (**Chapters 12 and 13**). Examples include mechanical damage to the seafloor and benthic communities due to drilling rig or platform installation; attraction of fish to submerged structures; burial and smothering of benthic organisms by drilling fluid and cuttings discharges; shading of benthic macroalgae and seagrasses by turbid water during drilling fluid discharges; and localized contamination of bottom sediments with trace metals and hydrocarbons from routine discharges.

If no shore base or pipeline landfall were to be located in the study area, there would be no direct mechanism for routine activities to affect coastal environments and organisms. Onshore facilities can affect coastal environments through habitat destruction (resulting from construction activities) and increased vessel traffic in coastal waters. The most likely locations for a shore base outside the study area, Port Everglades and Port Manatee, are developed industrial ports where construction and vessel traffic would pose less of an environmental problem.

The organisms most likely to be affected by routine operations are benthic organisms that live within a fixed radius (e.g., a few hundred meters) of drill sites and pelagic organisms (such as fishes and possibly sea turtles) that may be attracted to OCS structures. Effects on planktonic populations are naturally mitigated by the short residence time of water masses at a particular site of disturbance (e.g., drilling rig or platform) and by the short generation time of most phytoplankton and zooplankton. For other pelagic organisms, including various marine mammals, sea turtles, and birds that might encounter OCS structures occasionally, the chance of a significant effect on populations from a few structures in the study area is slim.

Local environmental effects are mainly of concern if OCS activities are carried out near especially rare, valuable, and/or sensitive ecosystems. The Florida Reef Tract is a prime example of such a system (**Chapter 4**). The Reef Tract encompasses the only living, shallow-water coral reef in the continental U.S., which is of enormous aesthetic, ecological, and economic value. The study area also includes a diverse array of hard bottom and soft bottom communities and deepwater seagrass (*Halophila*) meadows (**Chapter 5**). Seagrass meadows and hard bottom areas colonized by sessile epifauna are defined as live bottom and are automatically considered valuable and sensitive by the MMS and the State of Florida. However, although these communities have been studied enough to determine their relative rarity or commonness, virtually nothing is known of their ecological importance, economic value, or sensitivity to physical disturbance and sedimentation (**Chapter 5**).

The effects of unrestricted, routine OCS drilling and production activities on coral reefs cannot be predicted with confidence. However, it is clear that the potential for damage exists and that reefs can be protected through a few, simple measures. Physical and mechanical damage to coral reefs has been documented around exploratory well sites drilled over 25 years ago near the Marquesas Keys (Shinn et al. 1989; see **Chapters 12 and 13**). No lasting effects other than physical and mechanical damage were detected in that study, and Shinn et al. (1989) argue that modern environmental restrictions on drilling operations would have prevented the observed damage (i.e., placement of drilling rigs on coral reefs would not be permitted). Elsewhere in the Gulf of Mexico where drilling has occurred near coral reefs (e.g., at the Flower Garden

Banks off the Texas coast), discharge restrictions and establishment of a "no-activity zone" have prevented physical/mechanical and chemical damage to the reefs (**Chapters 12 and 13**).

Quantitative monitoring of deepwater seagrass (*Halophila*) beds on the West Florida shelf has shown that seagrass within several hundred to several thousand meters of an exploratory drill site could be affected by drilling discharges (**Chapter 13**). The persistence of drilling effects could not be determined from that study because a hurricane destroyed all deepwater seagrass beds (they returned the following growing season). Seagrass mortality would be of much greater concern in South Florida climax seagrass beds because the seagrasses do not reappear seasonally. According to Zieman (**Chapter 4**), any reduction in light (e.g., due to drilling discharges) can be considered detrimental to seagrasses.

There has been no quantitative monitoring of eastern Gulf of Mexico benthic communities (other than deepwater seagrass beds, as noted above) in connection with OCS activities. Qualitative visual observations of an exploratory drill site off Southwest Florida indicate little or no damage to the benthic environment (**Chapter 12**). Results of benthic monitoring programs in other OCS areas indicate generally localized and minor effects on benthic communities around drilling rigs and platforms (**Chapter 13**). However, these studies are of limited usefulness for predicting effects in South Florida because of the unusual nature of the benthic communities here (especially the importance of light-dependent biota such as macroalgae, seagrasses, and corals). Monitoring programs conducted at the Flower Garden Banks in the northwestern Gulf of Mexico provide no useful information because drilling restrictions prevented exposure of corals and other light-sensitive benthic biota to drilling effluents.

Mitigation Measures. Three main regulatory mechanisms exist that can avoid, minimize, or lessen environmental damage to benthic communities from routine operations in OCS waters. The most powerful option is to defer (exclude) from leasing blocks that contain biota or ecosystems of special concern. Specific deferrals normally occur at the lease sale stage, but two areas (the Key Largo and Looe Key National Marine Sanctuaries) were identified for deferral in the 5-Year Program Environmental Impact Statement under the (now cancelled) Straits of Florida lease sale (MMS 1987a). A second option is to attach biological stipulations to leases, requiring protection of certain types of habitats or biota if they occur within lease blocks. A third tool for protecting specific ecosystems is the National Pollutant Discharge Elimination System (NPDES) permitting process under which all OCS discharges are regulated by the U.S. Environmental Protection Agency (EPA). Under NPDES permits issued to operators, the EPA can limit or prohibit discharges near coral reefs, seagrass beds, live bottom areas, or similar ecosystems (**Chapter 13**). Other protective measures are cited in **Chapter 12.**

Lease sale deferrals would be the simplest and most effective way to protect the Florida Reef Tract and associated seagrass beds in Hawk Channel. Because locations of the major coral reefs and seagrass beds are known, it would be a simple matter to identify lease blocks for deferral. These blocks constitute a small fraction of the total acreage within the Straits of Florida Planning Area; however, the blocks constitute a significant fraction, perhaps 20%, of the total acreage inshore of the 200-m isobath.

Lease stipulations are a more feasible means to protect offshore benthic communities. Because the distribution of these communities is not known on a block-by-block basis, there is not enough information to map potential deferral areas in advance

of leasing.[2] A lease stipulation could require operators to conduct visual and geophysical surveys of each block prior to drilling operations. The MMS and the State of Florida could use this information to evaluate the need for protective measures on a case-by-case basis. For example, under the existing live bottom stipulation to eastern Gulf of Mexico leases, operators can be required to relocate drill sites, transport drilling fluids and cuttings to an approved disposal site (rather than discharge at the site), or monitor biological effects (**Chapter 12**).

In connection with lease stipulations, it would seem reasonable to include the option of "no drilling allowed" if an entire lease block were found to be characterized by an unusually rare or productive offshore benthic community.[3] However, under the existing live bottom stipulation attached to leases in the Eastern Gulf of Mexico Planning Area, there is no provision for prohibiting drilling altogether. This is different from the situation in the Central and Western Gulf of Mexico Planning Areas, where stipulations to certain leases contain provisions for "no-activity zones" around high-relief offshore banks, some of which contain coral communities. The different treatment probably reflects industry economic considerations as well as differences in perceived value and rarity of the benthic communities. That is, because the location of the high-relief banks in the central and western Gulf is well known, a petroleum company would know in advance of leasing that activities would be restricted or prohibited in certain areas. This would not be the case in the study area, where the nature of benthic communities within a lease block would not be known until a company expended money leasing the block and conducting visual surveys. On strictly *environmental* (rather than *economic*) grounds, there is no reason to exclude the possibility of prohibiting drilling from the list of options in a lease stipulation.

As noted in **Chapter 5**, there is little or no information upon which to base case-by-case decisions concerning protection of offshore benthic communities in the study area. Little is known of the ecological or economic value of these communities or their sensitivity to OCS operations. Therefore, at present, such decisions are likely to be based on information about the relative rarity of these communities and their apparent productivity (e.g., density of epibiota).

Accidents

Accidental oil spills are the foremost public and scientific concern about OCS leasing off South Florida. Large ($\geq$1,000 barrels) and very large ($\geq$100,000 barrels) oil spills are rare events; nevertheless, they do occasionally occur during OCS operations (**Chapter 12**). Therefore, it is important to consider the potential effects of oil spills in decisions about OCS leasing in the study area.

A large spill could result from a blowout or other platform accident, a vessel collision, or an accident during transfer or transport operations. In the study area, there is already a risk of spills from tankers and other large ships passing through the Straits

[2]MMS studies of the Southwest Florida shelf provide only a general idea of the distribution of benthic communities, although the location of some specific communities is known (see **Chapter 5**). Block-by-block surveys of the entire study area in advance of leasing would not be practical.

[3]An example would be the deep *Agaricia* reef located northwest of the Dry Tortugas, or portions of the deep reef located offshore of the Florida Reef Tract (see **Chapter 5**).

of Florida. The existing spill risk from tankers probably would be greater than the risk from OCS production, unless huge new reserves were discovered (**Chapter 12**).[4]

Proponents of offshore drilling argue that extraction of domestic reserves from the OCS will reduce the risk of oil spills from tankers carrying imported oil. Although this ought to be true for the Nation as a whole, it is not necessarily so for the study area, in part because of the varied sources and destinations of tankers passing through the Straits of Florida (**Chapter 12**). If economically recoverable quantities of oil were found in the study area, then OCS operations would *increase* the risk of spillage. For geological reasons, there is little chance of a blowout offshore South Florida; spills would be more likely to occur during the transfer of oil from platforms to tankers and during the transportation of oil to refineries (**Chapter 12**).

Effects. Results of accidental and experimental spills in tropical and subtropical habitats indicate that oil spills can cause severe damage to mangrove forests, coral reefs, seagrass beds, and associated biota (**Chapter 15**). Populations of sea turtles, birds, and manatees, as well as larvae (ichthyoplankton) of commercially and recreationally important fishery species, are sensitive to oiling and could be seriously affected. Some of the individual species of concern have been discussed in previous sections.

Because of highly publicized spills such as *Exxon Valdez*, it is easy to imagine the worst in the event of a single, large oil spill in the study area. Yet the severity and extent of damage in the study area cannot be predicted with confidence because of the large number of variables affecting the fate of an oil spill. These variables include the location and size of the spill; the type of oil spilled; wind, wave, and current conditions; temperature; and the effectiveness of oil spill response measures.

The Loop Current can have a powerful influence on the fate of an oil spill off South Florida (State of Florida and MMS 1989). Depending on the circumstances, the Loop Current could expose much of the study area to spilled oil, or transport the oil out of the study area before it could hit the coast. Trajectory simulations show that the Loop Current can rapidly transport oil spilled on the Southwest Florida shelf (north of the study area) around to the Lower Keys, Reef Tract, and Southeast Florida coast (State of Florida and MMS 1989). Once it reaches the Straits of Florida via the Loop Current, oil can impinge upon coastal areas through eddy or meander formation, or through winds blowing across the axis of the main current. In some of the cases simulated by the State of Florida and MMS (1989), oil was entrained in the Loop Current, carried around to the Straits of Florida, and blown back through the Florida Keys, reaching Florida Bay and the Southwest Florida coast faster by this indirect route than by direct, onshore transport from a nearby launch point.

Because spill trajectories reported by the State of Florida and MMS (1989) depend heavily on the launch point, the results cannot simply be extrapolated to the study area. However, it is evident that spills from some launch points in the study area could reach oil-sensitive environments within a few hours. Given such a short time, it would be difficult or impossible to prevent a slick from reaching oil-sensitive environments. In addition, it would be difficult or impossible to clean up spilled oil in some areas, such as the Ten Thousand Islands, Florida Bay, and the Lower Keys (**Chapter 15**).

[4]In addition, tankers (or other ships carrying fuel oil) could bring the spill risk directly to coastal habitats by grounding on reefs. During one three-week period in October-November 1989, three freighters grounded on South Florida reefs in the Florida Keys and Dry Tortugas (**Chapter 4**). All three carried large quantities of fuel oil, but fortunately, none of their tanks ruptured.

Large oil spills are rare events, but their potential for damage in the study area is of special concern because of the limited time that would be available to respond to a spill before oil could reach a variety of highly valued, oil-sensitive environments.[5] The extent and severity of damage from a single, large oil spill in the study area cannot be predicted with confidence, because of the large number of variables involved. Based on a review of historical spills and the available information about spill trajectories, the potential exists for extensive damage to mangrove forests, coral reefs, seagrass beds, and associated biota (**Chapter 15**). Little is known about how long it might take for mangroves, coral reefs, or seagrass beds to recover from a major oil spill; however, estimates range into the tens to hundreds of years (**Chapter 15**).

Mitigation Measures. Protective measures are in effect during OCS operations to minimize the chance of an oil spill and to minimize environmental damage in the event of a spill. Additional, specific measures to reduce the risk of spillage off South Florida have been presented by the State of Florida and MMS (1989). However, no regulations or precautions can prevent all accidents. In addition, the adequacy of existing plans, personnel, and equipment to handle a large or very large spill in the study area is unknown.

The mishandling of the recent *Exxon Valdez* spill in Alaska has called into question the adequacy of existing oil spill contingency plans nationwide (**Chapter 12**). In the aftermath of the spill, spill contingency plans in South Florida and other parts of the country are under review by Federal and State governments, as well as the petroleum industry. According to the Petroleum Industry Response Organization (PIRO), no existing oil spill response cooperative is equipped to handle spills larger than 25,000 barrels in the open ocean, or 40,000 barrels in coastal waters (PIRO Steering Committee 1990). The petroleum industry is working to develop the capability to respond to spills as large as 216,000 barrels, but this capability will not be in place for several years (PIRO Steering Committee 1990).

A protective measure that has been used previously in the eastern Gulf of Mexico is the establishment of a nearshore buffer zone, which is deferred (excluded) from leasing. The purpose is to keep some minimum distance between potential spill sources and the coast, thereby allowing additional time for natural degradative and dispersive processes and human response measures to prevent spilled oil from reaching sensitive environments or to minimize potential damage. In recent eastern Gulf of Mexico lease sales, the MMS deferred a 37 to 56 km (20 to 30 nmi) buffer zone along the West Florida coast (MMS 1987c).

A similar approach is being followed with respect to tanker traffic in the Straits of Florida, which poses a significant risk of a large oil spill (**Chapter 12**). Florida's Governor recently obtained a voluntary agreement with 15 oil companies whereby their tankers would remain at least 18.5 km (10 nmi) offshore during passage through the Straits, to minimize the chance of a spill resulting from a ship grounding. At the request of the Governor and the President, the U.S. Coast Guard will be proposing a similar avoidance zone in June 1990 to the International Maritime Organization.

The size of the existing OCS leasing buffer zone off West Florida does not have any specific scientific rationale. An appropriate size for a buffer zone in the study area could be estimated through simulation modeling and a comprehensive evaluation of

[5]The minimum distance to land in the Straits of Florida Planning Area is 5.6 km (3 nmi), corresponding to the Three Mile Line. In the Eastern Gulf of Mexico Planning Area, the minimum distance is 16.7 km (9 nmi), corresponding to the Three League Line. Portions of the Florida Reef Tract are in Federal waters, up to 13 km (7 nmi) offshore.

contingency plans (**Chapter 12**). Modeling could be used to estimate the minimum time for oil to reach shore (or other targets) from various hypothetical launch points. Oil spill contingency plans could be evaluated to determine the minimum time within which it would be possible to respond effectively to various sizes of spills. The combination of information would allow decision-makers to identify areas within which effective oil spill response would not be feasible.

Because the continental shelf in the Straits of Florida Planning Area is narrow, adoption of a nearshore buffer zone could severely restrict the area suitable for drilling. The distance from the Three Mile Line to the 200-m isobath ranges from about 5 to 45 km (3 to 24 nmi). A 37 km (20 nmi) buffer zone would exclude nearly all of the area within the 200-m isobath from leasing. Farther offshore, deep water, strong currents, and heavy ship traffic would make drilling operations expensive and possibly dangerous. A 37 km (20 nmi) buffer zone would also exclude from leasing most of the Eastern Gulf of Mexico Planning Area within the present study area.

Effects on Submerged Cultural Resources

Routine Operations

Effects. Oil and gas operations can affect cultural resources in a variety of ways, not the least of which is the positive effect of discovery when it occurs in the course of implementing standard MMS procedures during the several phases of oil and gas operations (**Chapter 10**).

The main threat to prehistoric and historic resources from routine operations is physical damage or loss of integrity through mechanical processes (e.g., rig or platform installation). Additionally, some routine discharges could modify the existing preservation regime through a change in the chemistry of the matrix within which the resources exist.

Mitigation Measures. The MMS has procedures in place for the consideration of cultural resources at all stages of oil and gas development. These procedures include Notices-to-Lessees for cultural resource surveys, in-house review of cultural resource reports, and the MMS *Handbook for Archaeological Resource Protection.*

Effects of mechanical processes may be limited or even disregarded if the protecting sediment is not disturbed (**Chapter 10**). Thus, detection of the resource is the key to avoiding damage. Routine archeological surveys and interpretive reports required by the MMS for leases in water depths <45 m should be adequate to ensure detection and avoidance of most submerged cultural resources. A new lease stipulation in preparation by the MMS Gulf of Mexico OCS Region would reduce line spacing from 150 m to 50 m for historic cultural resource surveys (**Chapter 10**). This measure should improve detection of older shipwrecks.

Cooperation and coordination between Federal and State agencies could help to preserve and protect submerged cultural resources in the study area in the event that offshore oil and gas operations proceed (**Chapter 10**). For example, the State of Florida is developing a *Comprehensive Historic Preservation Plan* (currently in draft) that could become an integral component of the management of cultural resources on the South Florida shelf. The MMS should work with the State of Florida to develop detailed procedures for the exploration for, reporting of, evaluation of, and data recovery from archeological sites.

Accidents

Effects. Oil spills could affect radiocarbon datability of preserved archeological remains and modify preserving anaerobic environments. Oil spills could also affect site-protecting flora common along the mainland shoreline of the study area.

Mitigation Measures. Measures to lessen the risk of oil spills have been discussed above. No protective measures can be foolproof. As recommended in **Chapter 10**, the State of Florida and the MMS could develop joint working agreements, procedures, and policies for handling oil and chemical spills that may affect cultural resources.

Effects on the Economy

Routine Operations

Effects. Among the State of Florida's major concerns about proposed offshore drilling and production is that these activities will degrade the coastal environment and thereby jeopardize the region's economic base in fisheries, recreation, and tourism (**Chapter 16**).

The economic benefits of OCS leasing are national in scope and flow to all regions of the country (**Chapter 16**). The experience of previous OCS leasing indicates that the expected net social benefits of leasing off South Florida would be positive, both for Florida and the Nation.

Based on the resource estimates developed by the MMS, it is unlikely that extensive onshore development would be necessary in the study area. In fact, as noted earlier in this chapter, it is unlikely that *any* OCS support facilities would be located in the study area. For this reason, no onshore development effects are likely unless the situation changes such that onshore facilities are going to be located in the study area.

Other aspects of routine OCS operations having potential socioeconomic effects include space-use conflicts with fisheries (e.g., shrimp trawling on the Tortugas grounds), degradation of air and water quality, and the presence of offshore structures *per se* (an aesthetic consideration if they are visible from shore). Based on the limited scope of OCS operations projected by the MMS, these aspects are not expected to pose significant economic problems.

Mitigation Measures. No specific measures are proposed to mitigate potential socio-economic effects (**Chapter 16**).

Accidents

Effects. Oil spills could affect the region's economy by temporarily fouling tourist beaches, damaging commercial and recreational fisheries, and reducing property values. According to an MMS analysis, the per-barrel social costs of oil spills in South Florida would be higher than in any other OCS Planning Area (MMS 1987b). The most difficult costs to estimate are those resulting from damage to the natural environment. Many people would question the validity of placing a specific dollar value on an estuary, a mangrove community, or the life of a seabird or manatee (**Chapter 16**). In the unlikely event of a very large oil spill, the costs might approach or exceed the economic benefits.

Mitigation Measures. No specific measures are proposed to mitigate potential socio-economic effects (**Chapter 16**). However, measures discussed above to reduce the likelihood of oil spills and to minimize the resulting damage are obviously applicable.

EVALUATION OF INFORMATION NEEDS

Each author was asked to identify gaps in knowledge of the South Florida environment. Of the data gaps discussed in previous chapters, some pertain to oil and gas operations, whereas others are of a more general nature. The purpose here is to highlight those that are most critical for making decisions about OCS leasing.

The question of "adequacy" of information for leasing decisions is not addressed formally here, as the topic is beyond the scope of this report. Information adequacy has been discussed recently by the National Research Council (NRC) (1989) in connection with proposed lease sales off California and Southwest Florida. It is evident from the NRC report that there is no widely held standard of information adequacy for OCS leasing decisions. This is in itself a significant problem that needs to be addressed.

The most significant data gap overall is the lack of knowledge of oil and gas resources in the study area. The magnitude of these resources will determine the level of development, which in turn will determine the environmental, economic, and social consequences. The accuracy of resource estimates developed by the MMS and others cannot be known until exploratory drilling is conducted.

Given that information about resource potential is critical, one way to improve the data base for decisions would be to allow limited evaluation and exploratory drilling--not necessarily in the study area, but somewhere in the offshore South Florida Basin. These activities involve little risk of environmental damage. Unfortunately, this approach poses several problems, not the least of which is the widespread perception that once the first step is taken, there will be "no turning back"--i.e., development and production operations with greater environmental risks will inevitably be allowed if commercial quantities of oil and gas are found (NRC 1989). Therefore, it is likely that OCS decisions will continue to be made on the basis of incomplete information about the resource base and development plans. In that context, specific information needs are discussed below.

Geology

Two geological topics are particularly important for decisions about oil and gas leasing: (1) petroleum potential; and (2) geologic hazards and operational constraints.

Enough is known about petroleum geology to indicate the potential for commercially recoverable hydrocarbons in the study area (**Chapter 2**). Resource estimates and probabilities of discovering hydrocarbons have been developed by the MMS and others. However, whether commercially recoverable hydrocarbons actually are present, and in what amounts, cannot be known in advance of exploratory drilling.

Likewise, sufficient information is available to identify potential geologic hazards and operational constraints in the study area. There is no indication of geologic hazards that would pose a major problem; to the contrary, there appears to be a low potential for abnormal pressures that might result in a blowout.

A third role of geological data in decisions about OCS operations is to provide a framework for understanding the chemistry and biology of the study area. Existing information is adequate to describe the geologic framework of South Florida and to provide a basis for subsequent discussions concerning petroleum activity in the study area. Two kinds of data gaps have been identified: (1) incomplete geographic coverage (e.g., lack of information for the Southwest Florida shelf between Cape Sable and the Dry Tortugas) and (2) lack of information on processes controlling geologic development. Studies of these topics would aid in understanding the study area, but are not considered critical for leasing decisions.

Chemistry

Information about the chemical environment is important in two main respects for decisions about OCS leasing. First, trace metal and hydrocarbon data help to indicate the level of anthropogenic contamination in the study area. This is important in predicting whether routine OCS operational discharges and accidental spills would be detectable in the water, sediments, and organisms of the study area. The level of existing pollution is also a consideration in evaluating biological effects of OCS operations. Second, information on transformations and degradation of hydrocarbons is needed to predict the fate and effects of oil spills.

Existing data indicate that the study area is characterized by low concentrations of trace metal and petroleum hydrocarbon contaminants, with the exception of floating and dissolved oil residues in the Straits of Florida and localized trace metal elevations around sites of human activity (**Chapter 3**). Additional baseline data are not critical for leasing decisions; however, because of the poor or questionable quality of some trace metal data, additional analyses of sediments and benthic organisms should be conducted before drilling operations proceed. Background concentrations of potentially toxic trace metals should be determined in sediments and a few species of benthic organisms collected well away from harbors, sewage outfalls, power plants, or other sites of human activity. These concentrations are needed for comparison with values determined after drilling.

Little is known about transformations and degradation of oil in tropical/subtropical environments (**Chapter 3**). Continuing study of the Bahia las Minas spill in Panama (Burns and Knap 1989; Jackson et al. 1989) will help in this regard. The lack of data on this topic does not preclude decisions based on the assumption that spilled oil can persist long enough to reach oil-sensitive shorelines. However, additional data would help to refine scenarios of oil spill fate and effects in South Florida.

Biology

Information about biological effects of OCS operations is critical to decisions about OCS leasing. In order to predict effects, one needs to know the location of principal ecosystems, communities, and organisms that might be exposed to physical disturbance, chemical contamination, or other agents of change. Some understanding of seasonality and other natural and anthropogenic variability is necessary in order to discern effects of OCS operations. Knowledge of ecological relationships within communities and ecosystems is required in order to predict in detail the consequences of environmental damage. Information about sensitivity to mechanical disturbance, oil, operational discharges, and other agents of change is needed.

Coastal and Nearshore Communities

The general locations of the principal coastal and nearshore communities, namely mangrove forests, coral reefs, and seagrass beds, are known well enough that they could be avoided during routine operations. In addition, locations are known well enough that if the trajectory of a particular oil spill were known, one could predict whether a mangrove forest, coral reef, or seagrass bed were going to be hit.

In spite of the obvious ecological and economic importance of South Florida's mangrove forests, coral reefs, and seagrass beds, little more than the outline of their ecology is known (**Chapter 4**). These communities are subject to numerous natural and anthropogenic stresses at present. Because there have been no long-term studies of these communities in the study area, it would be difficult to separate effects of OCS operations (other than catastrophic damage) from the effects of random climatic events and anthropogenic stresses.

If the basic ecology of these communities is not well understood, then it follows that the consequences of environmental damage cannot be fully anticipated. The most important aspect of this problem is predicting recovery time. Ecological recovery can be defined as a return to the original structural and functional condition with the original species present (**Chapter 15**). Unless the original structural and functional relationships are understood, then it is not possible to predict the course of recovery.

The importance of the recovery issue has also been recognized by Boesch et al. (1987), who identified residual damage to biogenically structured communities such as wetlands, reefs, and vegetation beds as a high-priority topic for further research in relation to long-term effects of OCS operations. This concern is especially relevant to the South Florida area.

Further studies of the basic ecology of South Florida coastal and nearshore communities, including recovery from natural sources of disturbance such as hurricanes, can be helpful in this regard. In addition, continued, long-term study of spills in similar environments (e.g., the Bahia las Minas spill in Panama) can help to provide relevant data.

Offshore Benthic Communities

Much information is available concerning the general distribution of benthic habitats on the Southwest Florida shelf, but little information is available for the Straits of Florida shelf offshore of the Florida Reef Tract (**Chapter 5**). Systematic geophysical and visual surveys of this area are needed prior to leasing. Even if such surveys are conducted, photodocumentation surveys of individual lease blocks are likely to be required by the MMS prior to drilling in either area because of the scattered, mosaic nature of benthic communities off South Florida.

The general distribution of offshore benthic communities may be known (or refined in advance of drilling) well enough to protect certain communities on the basis of their relative rarity. However, little is known about the ecological importance or economic value of most of these communities, or their sensitivity to physical disturbance, sedimentation, and chemical contamination. Therefore, decisions at present are likely to be based on information about the relative rarity of these communities and their apparent productivity (e.g., density of epibiota). More information concerning benthic productivity, trophic relationships, and links to existing or potential fisheries would improve the management framework. If drilling does occur in the study area or in adjacent areas of the Southwest Florida shelf, effects on benthic communities should be monitored quantitatively in order to gain information that could be used to decide on future regulations and protective measures.

Plankton

Numerous shortcomings in the existing plankton data base were noted in **Chapter 6**. The most critical topic for further research is ichthyoplankton. Most species of commercially and recreationally valuable fish have pelagic eggs that undergo initial development in surface waters (as ichthyoplankton), where they would be susceptible to oiling. Because of the restricted nature of seasonal spawning and the concentration of eggs and larvae over spawning grounds and nursery areas, nearshore and estuarine fish populations could be very susceptible to damage by oil reaching coastal waters.

There are virtually no data on standing stock or production of ichthyoplankton off Southwest Florida (**Chapter 6**). Broad-scale sampling of the neuston and water column for ichthyoplankton would be necessary to fill regional and temporal gaps left by the few

studies that have been conducted in the study area. Over the longer term, data from these baseline surveys could be used to pinpoint areas and periods of special interest (e.g., nursery areas, periods and depth zones of highest spawning activity and larval abundance).

Fish Communities and Fisheries Biology

There is a great deal of information available about the families and species of fish associated with South Florida marine habitats. However, little quantitative information is available on community structure, trophic relationships, nutrient cycling, larval recruitment, transfer of materials and energy among habitats, and stability (**Chapter 7**).

From the standpoint of OCS oil and gas activities, there are two main concerns about fishes. First, certain groups are attracted to offshore structures, which serve as artificial reefs. A large body of information from the northwestern Gulf of Mexico can help to predict effects in the study area. Also, investigations of artificial reefs in and near the study area would provide relevant data. If many rigs and platforms are to be installed in the study area, then the implications for South Florida recreational and commercial fisheries will need to be evaluated in the context of existing fishery management plans.

A second major concern about OCS operations is that oil spills could damage fish populations, including stocks of commercially and recreationally valuable species. Direct effects on adult populations (i.e., fish kills) are of less concern than indirect effects resulting from (1) mortality to eggs and larvae (ichthyoplankton) in restricted coastal waters and (2) damage or destruction of nursery habitat (e.g., mangroves and seagrass beds). The critical information needs are (1) information about the distribution and abundance of ichthyoplankton, and (2) information about long-term effects of oil spills on coastal and nearshore communities that serve as nursery grounds. Information is lacking on both topics, as discussed above.

Marine Mammals and Sea Turtles

Species of marine mammals and sea turtles that may be found in the study area are known. However, little is known about the at-sea distribution of any of the cetaceans or sea turtles; most of the available data are from strandings, rather than sightings (**Chapter 8**). Certainly, those species that inhabit coastal areas (manatees) or nest on area beaches (loggerhead sea turtles) are most vulnerable to damage from an oil spill. However, effects on other species should not be discounted simply because little is known about when, where, or how many individuals are present in the study area. The information base on marine mammals and sea turtles could be improved through systematic aerial and shipboard surveys, as well as telemetry studies of selected species (**Chapter 8**).

Coastal and Marine Birds

Species of birds that occur, either seasonally or year-round, in the study area, are known (**Chapter 9**). In general, the species that are most at risk from a single, large oil spill can be identified (see above).

A major data gap that makes it difficult to evaluate the importance of local populations is that little is known about the total numbers of most North American bird species. For example, there are few, if any, population estimates for wading birds, shorebirds, raptors, etc. The importance of this information is obvious: if the overall size of a species population is unknown, how can the significance of mortality to a

breeding colony in the study area be evaluated? For many years, good estimates of waterfowl populations have been available from continent-wide censuses (**Chapter 9**). Similar censuses of larger wading birds, and perhaps other species, would aid in the evaluation of environmental effects, not just in South Florida but in other OCS areas.

The avifauna of South Florida's inshore, littoral, salt marsh, mangrove, and marine-interfacing inland habitats is well known in terms of general life history and seasonality of occurrence. However, information is lacking about frequently-occurring offshore pelagic birds, which are most likely to encounter spilled oil from tankers. This information could be gathered by surveying oceanic transects as suggested in **Chapter 9**. Also, from an oil spill response viewpoint, it would be useful to prepare an atlas of seabird breeding islets, rocks, pinnacles, etc. for the Straits of Florida.

Submerged Cultural Resources

For leasing decisions, it is important to know the types and possible locations of submerged cultural resources in the study area. Knowledge of submerged cultural resources in the study area is incomplete, but the basic picture is evident (**Chapter 10**). Both prehistoric and historic artifacts may be encountered during OCS operations. Prehistoric sites are likely to occur in water depths <50 m; shipwrecks may be found throughout the continental shelf, though concentrated in shallower water.

Limitations in the existing archeological data and models require that investigators look carefully at every possible location that may have cultural resource potential. Additional studies could refine the predictive models, leading to a marked increase in our understanding of human use of the shelf. This is not critical for leasing decisions, but it would allow analysts in the future to perform project-specific assessments more cost-efficiently.

Socioeconomics

Existing data provide a basic understanding of the study area's social and economic characteristics (**Chapter 11**). However, there are two areas in which additional data would help to provide a better basis for leasing decisions (**Chapter 16**).

First, there have been no sociological studies of the effects of OCS development on South Florida communities. Sociological studies of the possible effects of OCS leasing on a community such as Key West would answer at least some of the questions raised in the NRC (1989) report about information adequacy. Such studies possibly would also permit a policy evaluation of the validity and usefulness of this type of analysis.

Second, a potentially important category of economic costs has not been included in the estimates presented in **Chapter 16**. Little or no information exists concerning the user and non-user damages that would be sustained in the event of a degradation of special environments such as mangrove forests, coral reefs, and seagrass beds. This should be a high priority for future research. Questions concerning the "existence," "preservation," and "option" values of important environmental assets will continue to be raised. Because this category of environmental damages incorporates a large part of the general public's concern over OCS leasing, it seems appropriate to conduct studies of this topic, even though reservations will continue to be expressed concerning the meaning and validity of these categories of damage.

RECOMMENDATIONS

Mitigation Measures

Several measures to avoid, minimize, or lessen environmental effects of OCS operations have been discussed above. The following measures are considered most important:

1. Contingency plans to deal with large oil spills in the study area should be evaluated comprehensively. Measures to minimize the risk of spills and to maximize the amount of time available to respond before oil reaches the shoreline or other sensitive environments (e.g., mangrove islands, coral reefs, seagrass beds) should be evaluated. Because of heavy tanker traffic in the Straits of Florida, this review is needed regardless of whether OCS leasing occurs in the study area.

   As part of the evaluation of contingency plans, oil spill trajectories should be simulated from a variety of launch points. The simulations should not be narrowly focused on *contact probabilities*, as has been the case in previous MMS spill risk analyses. (Statistics are of little use for predicting whether a particular target will be hit, if only one or a few spills are anticipated.) Instead, the simulations should be used to determine general patterns of oil transport, estimate minimum times for oil to reach various shoreline segments and other resources, and estimate the potential areal extent of spill damage. Information concerning the minimum time for oil to reach shore would be of great value for contingency planning purposes. This information could be used, in conjunction with a comprehensive review of spill response capabilities, to identify areas where effective oil spill response would not be feasible. Such areas could be considered for designation as buffer zones (i.e., areas where OCS operations, and perhaps other spill-generating activities such as tanker traffic, would be prohibited).

2. Deferral (exclusion) from leasing of the Florida Reef Tract and adjacent climax seagrass beds should be considered as an option to protect these communities from the near-field effects of routine operations. If these areas are not deferred, other measures such as protective lease stipulations and discharge limitations should be used, as needed, to avoid or minimize damage.

3. To protect benthic communities in Federal waters, biological stipulations similar to those currently in effect on leases in the Eastern Gulf of Mexico Planning Area should be applied to leases in the study area. However, the stipulations should include the possibility of prohibiting drilling altogether in a lease block, in the event that there is no way to avoid damage to a particularly valuable, sensitive, or rare community discovered in the block.

4. Federal and State agencies should work together to develop agreements and procedures to enhance protection of submerged cultural resources in the study area. The State of Florida's *Comprehensive Historic Preservation Plan* (currently in draft) should become an integral component of the management of cultural resources on the South Florida shelf. In addition, the State of Florida and the MMS should develop joint working agreements, procedures, and policies for handling oil and chemical spills which may affect cultural resources.

Studies

Numerous topics for further study have been discussed above in this chapter and in the other chapters. Studies listed below are most important to provide better information for OCS-related decisions. The first five involve research specifically related to OCS operations and effects.

1. A definition of "adequacy" of environmental information for OCS leasing decisions should be developed. There clearly is no widely held standard of information adequacy, yet this is a critical issue for South Florida, as well as other OCS areas.

2. Because of the large volume of vessel traffic passing through the Straits of Florida, potential hazards to navigation should be evaluated before any OCS structures are placed there. Up-to-date, accurate information about the volume of vessel traffic through the Straits of Florida will be needed for this evaluation.

3. Little or no information is available concerning oil or dispersant toxicity to South Florida fishery species such as pink shrimp, spiny lobster, stone crab, and queen conch, as well as eggs and larvae of commercially important finfish. Although some effects can be inferred from studies on related species, toxicological studies of South Florida species would aid in evaluating possible consequences of an oil spill.

4. If drilling does occur on the Southwest Florida shelf in or near the study area, effects on offshore benthic communities should be studied quantitatively through a statistically sound monitoring program. Recovery of damaged communities should be studied.

5. Many questions remain about long-term and chronic effects of large-scale production operations. Although the projected level of OCS development in the study area is small by comparison with the central and western Gulf of Mexico, this issue will need to be evaluated in detail if commercial quantities of oil and gas are discovered off South Florida. Possible study approaches have been outlined by Boesch et al. (1987).

Two groups of studies are listed below that involve more basic research. Studies in the first group are considered more important and are listed in the same order as topics appear in the report.

6. Transformations and degradation of oil in tropical/subtropical environments need further research in order to help predict the fate and effects of an oil spill in the study area.

7. Additional, basic ecological studies of South Florida coastal and nearshore communities are needed in order to predict the course and time-span of recovery from a large oil spill. Recovery from natural sources of disturbance, such as hurricanes, should be studied. In addition, long-term studies of spills in similar environments (e.g., the Bahia las Minas spill in Panama) should be continued.

8. Because the distribution of offshore benthic communities in the Straits of Florida Planning Area is not well known, systematic geophysical and visual surveys of the continental shelf should be conducted there prior to leasing. Even if these surveys are conducted, photodocumentation surveys of individual lease blocks will still be necessary in this area and on the Southwest Florida shelf because of the scattered, mosaic nature of offshore benthic communities (mixture of hard bottom and soft bottom communities).

9. Research on ichthyoplankton is needed because of the potential effects of an oil spill on eggs and larvae of commercially and recreationally important fishery species. There are virtually no data on standing stock or production of ichthyoplankton off Southwest Florida. Broad-scale sampling of the neuston and water column for ichthyoplankton would be necessary to fill regional and temporal gaps left by the few studies that have been conducted in the study area. Over the longer term, data from these baseline surveys could be used to pinpoint areas and periods of special interest (e.g., nursery areas, periods and depth zones of highest spawning activity and larval abundance).

10. Additional field surveys of marine mammals and sea turtles are needed, because little is known about the at-sea distribution of these animals in the study area. The information base on marine mammals and sea turtles could be improved through systematic aerial and shipboard surveys, as well as telemetry studies of selected species.

11. From an oil spill response viewpoint, it would be useful to prepare an atlas of seabird breeding islets, rocks, pinnacles, etc. for the Straits of Florida.

12. Information concerning the economic value of special environments such as mangrove forests, coral reefs, and seagrass beds should be a high priority for future economic research. Because the potential for damage to these environments is a large part of the general public's concern over OCS leasing, it seems appropriate to conduct studies of this topic, even though many people will still have reservations about the validity of placing dollar values on this kind of damage.

Studies listed below also involve basic research and would provide useful information, but are considered less important than those listed above. Studies are listed in the same order as topics appear in the report.

13. If OCS leasing does occur in the study area, background concentrations of trace metals and hydrocarbons should be determined in sediment and a few species of benthic organisms collected well away from harbors, sewage outfalls, power plants, or other sites of human activity. These concentrations are needed for comparison with values determined after drilling.

14. If future oil and gas resource estimates indicate that many rigs and platforms are likely to be installed in the study area, then the implications of these new "artificial reefs" for South Florida recreational and commercial fisheries will need to be evaluated in the context of existing fishery management plans.

15. It is difficult to evaluate the importance of mortality to some local bird populations because little is known about the total numbers of most North American bird species. For many years, good estimates of waterfowl populations have been available from continent-wide censuses. Similar censuses of larger wading birds, and perhaps other species, would aid in the evaluation of environmental effects.

16. Sociological studies of the possible effects of OCS leasing on a community such as Key West would answer at least some of the questions raised in the NRC (1989) report about information adequacy. Such studies possibly would also permit a policy evaluation of the validity and usefulness of this type of analysis.

REFERENCES CITED

Boesch, D. F., J. N. Butler, D. A. Cacchione, J. R. Geraci, J. M. Neff, J. P. Ray, and J. M. Teal. 1987. An assessment of the long-term environmental effects of U.S. offshore oil and gas development activities: Future research needs. In *Long-term environmental effects of offshore oil and gas development*, ed. D. F. Boesch and N. N. Rabalais, 1-53. New York: Elsevier Applied Science.

Burns, K., and A. Knap. 1989. The Bahia las Minas oil spill: Hydrocarbon uptake by reef building corals. *Mar. Pollut. Bull.* 20:391-398.

Jackson, J. B. C., J. D. Cubit, B. D. Keller, V. Batista, K. Burns, H. M. Caffey, R. L. Caldwell, S. D. Garrity, C. D. Getter, C. Gonzalez, H. M. Guzman, K. W. Kaufmann, A. H. Knap, S. C. Levings, M. J. Marshall, R. Steger, R. C. Thompson, and E. Weil. 1989. Ecological effects of a major oil spill on Panamanian coastal marine communities. *Science* 243:37-44.

Minerals Management Service. 1987a. *Proposed 5-year outer continental shelf oil and gas leasing program, mid-1987 to mid-1992. Final environmental impact statement.* OCS EIS/EA MMS 86-0127. Washington, DC: U.S. Government Printing Office.

Minerals Management Service. 1987b. *5-Year leasing program, mid-1987 to mid-1992. Detailed decision documents.* Washington, DC: U.S. Government Printing Office.

Minerals Management Service. 1987c. *Final environmental impact statement, proposed oil and gas lease sales 113/115/116, Gulf of Mexico OCS Region.* OCS EIS MMS 87-0077. New Orleans.

Minerals Management Service. 1989. *Mid-price scenario, estimates of undiscovered economically recoverable oil and gas resources as of July 1989, eastern Gulf of Mexico region.* Document dated 21 September 1989. New Orleans.

National Research Council. 1989. *The adequacy of environmental information for outer continental shelf oil and gas decisions: Florida and California.* Washington, DC: National Academy Press.

Petroleum Industry Response Organization Steering Committee. 1990. *Steering committee report and recommendations on the implementation of PIRO.* Washington, DC.

Shinn, E. A., P. A. Dustan, and B. H. Lidz. 1989. *Biological assessment of the impact of exploratory wells drilled offshore South Florida.* OCS Study MMS 89-0022. New Orleans: U.S. Department of the Interior, Minerals Management Service.

State of Florida and Minerals Management Service. 1989. *Oil spill risk assessment task force report.* Prepared for the Governor of Florida and the Secretary of the Interior.

U.S. Geological Survey and Minerals Management Service. 1989. *Estimates of undiscovered conventional oil and gas resources in the United States--A part of the nation's energy endowment.* Washington, DC: U.S. Government Printing Office.

APPENDIX A

INFORMATION COLLECTION

METHODS

Literature was supplied to the chapter authors according to their individual needs. Socioeconomic literature was collected by graduate students at the Florida State University under the direction of Dr. Philip Sorensen. Mr. David Snyder of Continental Shelf Associates, Inc. collected and distributed literature on all other topics.

Computer Searches

Shortly after the project began, a series of computer searches was run using the Lockheed DIALOG Information Retrieval Service. The following data bases were searched:

- Aquatic Science and Fisheries Abstracts
- BIOSIS Previews (Biological Abstracts)
- CA Search (Chemical Abstracts)
- Dissertation Abstracts
- GeoRef
- Meteorological/Geoastrophysical Abstracts
- National Technical Information Service (NTIS)
- Oceanic Abstracts
- Pollution Abstracts

Individual searches were limited to particular topics such as coral reefs, seagrasses, trace metals, etc. Appropriate data bases, years, and key words were chosen for each search, depending on the topic and the completeness of each author's literature files.

A search of the National Environmental Data Referral Service (NEDRES) data base was requested through the Washington office of NEDRES. This broad search for oceanographic data sets yielded few useful leads.

The results of the computer searches were distributed to the chapter authors as printouts or text files on disk. The authors were given the option of obtaining the documents from their local library or requesting that Mr. Snyder order the documents for them.

Telephone Contacts and Manual Searches

After the computer searches were completed, various Federal, State and local government agencies, universities, private organizations, and individuals were contacted for publication lists and information about relevant studies (**Table A.1**). The goal was to obtain lists of publications that might be of use to one or more authors, and to identify people and agencies that the authors might want to contact for more information. Publication lists, abstracts of papers and reports, and other information sources were passed on to the authors.

Most documents requested by the chapter authors were collected by ordering from Federal or State agencies or by borrowing publications through Interlibrary Loan. Additional documents were collected during two visits to the Rosenstiel School of Marine and Atmospheric Sciences library and government agencies in Miami. The Minerals Management Service (MMS) Atlantic and Gulf of Mexico OCS Regions both provided additional documents on request.

PREVIOUS STUDIES SPONSORED BY THE U.S. DEPARTMENT OF THE INTERIOR (USDOI)

USDOI agencies such as the Bureau of Land Management (BLM), MMS, U.S. Fish and Wildlife Service (USFWS), and U.S. Geological Survey (USGS) have sponsored numerous studies of the South Florida area. Some major studies and reports are highlighted below.

- Geological/geophysical studies of the Southwest Florida shelf and slope by the USGS (Holmes 1981).
- An ecological atlas of Southwest Florida (Kunneke 1983), accompanied by a narrative volume (Palik and Lewis 1983).
- A characterization of the Everglades, Florida Bay, and the Florida Keys (Schomer and Drew 1982), and a synthesis of information on the Caloosahatchee River/Big Cypress watershed (Drew and Schomer 1984).
- Community profiles of coral reefs (Jaap 1984), mangroves (Odum et al. 1982), and seagrasses (Zieman 1982).
- A map series depicting the Florida Reef Tract (Marszalek 1982).
- A literature review and annotated bibliography of estuarine areas of Florida (Mahadevan et al. 1984).
- Reports from a five-year study of benthic habitats on the Southwest Florida shelf (Continental Shelf Associates, Inc. 1987; Environmental Science and Engineering, Inc. et al. 1987). Also, a report from a subsequent study of deepwater seagrass beds and other nearshore habitats in the southwest Florida/Florida Bay region (Continental Shelf Associates, Inc. 1989).
- An analysis and summary of data on the distribution of fish and penaeid shrimp in the eastern Gulf of Mexico (Darnell and Kleypas 1987).
- Reviews of endangered and threatened plants (McCoy 1981) and vertebrates (Woolfenden 1983) in Southwest Florida.
- Reports on the distribution of marine mammals (Irvine et al. 1981; Schmidly 1981; Fritts et al. 1983). The latter report also covers sea turtles and marine birds. Also, Fritts and McGehee (1982) and Vargo et al. (1986) studied effects of petroleum on sea turtles.
- A three-volume summary of information on marine birds (Clapp et al. 1982a,b, 1983).
- Archeology/cultural resource studies for Key West to Texas (Coastal Environments, Inc. 1977) and Cape Hatteras to Key West (Science Applications, Inc. 1981).
- A synthesis of socioeconomic information for Southwest Florida (French and Parsons 1983).

There are many other sources of literature for the study area, including papers, reports, and theses from researchers at the University of Miami and the University of South Florida, and reports from the South Florida Research Center of the National Park Service. These and other references are cited in the subject chapters.

REFERENCES CITED

Clapp, R. B., R. C. Banks, D. Morgan-Jacobs, and W. A. Hoffman. 1982a. *Marine birds of the southeastern United States and Gulf of Mexico. Pt. I, Gaviiformes through Pelecaniformes*. FWS/OBS-82/01. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Clapp, R. B., D. Morgan-Jacobs, and R. C. Banks. 1982b. *Marine birds of the southeastern United States and Gulf of Mexico. Pt. II, Anseriformes*. FWS/OBS-82/20. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Clapp, R. B., D. Morgan-Jacobs, and R. C. Banks. 1983. *Marine birds of the southeastern United States and Gulf of Mexico. Pt. III, Charadriiformes*. FWS/OBS-83/30. Washington, DC: U.S. Fish and Wildlife Service, Division of Biological Services.

Coastal Environments, Inc. 1977. *Cultural resources evaluation of the northern Gulf of Mexico continental shelf*. Washington, DC: U.S. Department of the Interior, National Park Service, Office of Archeology and Historic Preservation, and Bureau of Land Management.

Continental Shelf Associates, Inc. 1987. *Southwest Florida regional biological communities survey, Year 3 final report*. OCS Study MMS 86-0109. Metairie: U.S. Department of the Interior, Minerals Management Service.

Continental Shelf Associates, Inc. 1989. *Southwest Florida nearshore benthic habitat study, narrative report*. OCS Study MMS 89-xxxx. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Darnell, R. M., and J. A. Kleypas. 1987. *Eastern Gulf shelf bio-atlas. A study of the distribution of demersal fishes and penaeid shrimp of the soft bottoms of the continental shelf from the Mississippi River Delta to the Florida Keys*. OCS Study MMS 86-0041. New Orleans: U.S. Department of the Interior, Minerals Management Service.

Drew, R. D., and N. S. Schomer. 1984. *An ecological characterization of the Caloosahatchee River/Big Cypress watershed*. FWS/OBS-82/58.2. Washington, DC: U.S. Fish and Wildlife Service, Division of Biological Services.

Environmental Science and Engineering, Inc., LGL Ecological Research Associates, Inc., and Continental Shelf Associates, Inc. 1987. *Southwest Florida shelf ecosystems study data synthesis*. OCS Study MMS 87-0023. New Orleans: U.S. Department of the Interior, Minerals Management Service.

French, C. O., and J. W. Parsons, ed. 1983. *Florida coastal ecological characterization: a socioeconomic study of the southwestern region*. FWS/OBS-83/14. Washington, DC: U.S. Fish and Wildlife Service, Division of Biological Services.

Fritts, T. H., and M. A. McGehee. 1982. *Effects of petroleum on the development and survival of marine turtle embryos*. FWS/OBS-82/37. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Fritts, T. H., A. B. Irvine, R. D. Jennings, L. A. Collum, W. Hoffman, and M. A. McGehee. 1983. *Turtles, birds, and mammals in the northern Gulf of Mexico and nearby Atlantic waters*. FWS/OBS-82/65. Washington, DC: U.S. Fish and Wildlife Service, Division of Biological Services.

Holmes, C. W. 1981. *Late Neogene and Quaternary geology of the southwestern Florida shelf and slope*. Open File Rep. No. 81-1029. Washington, DC: U.S. Geological Survey.

Irvine, A. B., J. E. Caffin, and H. I. Kockman. 1981. *Aerial surveys for manatees and dolphins in western peninsular Florida*. FWS/OBS-80/50. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Jaap, W. C. 1984. *The ecology of the South Florida coral reefs: A community profile*. FWS/OBS-82/08. Washington, DC: U.S. Fish and Wildlife Service, Division of Biological Services.

Kunneke, J. T. 1983. *Southwestern Florida ecological characterization: An ecological atlas*. FWS/OBS-82/47. Washington, DC: U.S. Fish and Wildlife Service, Division of Biological Services.

Mahadevan, S., J. Sprinkel, D. Heatwole, and D. H. Wooding. 1984. *A review and annotated bibliography of benthic studies in coastal and estuarine areas of Florida*. Contrib. Mote Mar. Lab., Vol. 2, No. 1. Sarasota.

Marszalek, D. S. 1982. *Florida reef tract marine habitat ecosystems (map series)*. New Orleans: U.S. Department of the Interior, Bureau of Land Management.

McCoy, E. D. 1981. *Rare, threatened, and endangered plant species of Southwest Florida and potential OCS activity impacts*. FWS/OBS-81/50. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Odum, W. E., C. C. McIvor, and T. J. Smith III. 1982. *The ecology of the mangroves of South Florida: A community profile*. FWS/OBS-82/24. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Palik, T. F., and R. R. Lewis III. 1983. *Southwestern Florida ecological characterization: An ecological atlas. Map narratives*. FWS/OBS-83/47. Washington, DC: U.S. Fish and Wildlife Service, Division of Biological Services.

Schmidly, D. J. 1981. *Marine mammals of the southeastern United States coast and the Gulf of Mexico*. FWS/OBS-80/41. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Schomer, N. S., and R. D. Drew. 1982. *An ecological characterization of the lower Everglades, Florida Bay and the Florida Keys*. FWS/OBS-82/58.1. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Science Applications, Inc. 1981. *A cultural resource survey of the continental shelf from Cape Hatteras to Key West*. Contract No. AA551-CT8-40. Washington, DC: U.S. Department of the Interior, Bureau of Land Management.

Vargo, S., P. Lutz, D. Odell, E. S. Van Vleet, and G. Bossart. 1986. *Study of the effects of oil on marine turtles*. OCS Study MMS 86-0070. Washington, DC: U.S. Department of the Interior, Minerals Management Service.

Woolfenden, G. E. 1983. *Rare, threatened, and endangered vertebrates of southwest Florida and potential OCS activity impacts*. FWS/OBS-82/03. Washington, DC: U.S. Fish and Wildlife Service, Division of Biological Services.

Zieman, J. C. 1982. *The seagrass ecosystems of South Florida: A community profile*. FWS/OBS-82/25. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.

Table A.1. Agencies and people contacted by Continental Shelf Associates, Inc. for environmental information about the South Florida area.*

Agency/Organization	Contact(s)
FEDERAL AGENCIES	
Minerals Management Service Atlantic OCS Region Herndon, VA	C. Anderson C. Benner R. LaBelle J. Lane J. Wilson
Minerals Management Service Gulf of Mexico OCS Region New Orleans, LA	G. Crawford R. Defenbaugh D. Elvers G. Goeke
National Energy Information Center Washington, DC	B. Horvath
National Environmental Data Referral Service Washington, DC	G. Barton
National Marine Fisheries Service Southeast Fisheries Center National Oceanic and Atmospheric Administration Miami, FL	K. Lindeman
National Park Service Biscayne National Monument Homestead, FL	T. Rutledge
National Park Service South Florida Research Center Homestead, FL	J. Tilmant T. Schmidt
U.S. Coast Guard Miami, FL	Capt. Witten
U.S. Fish and Wildlife Service Coastal Ecosystems Division Panama City, FL	L. Patrick
U.S. Fish and Wildlife Service National Wetlands Research Center Slidell, LA	Librarian
U.S. Geological Survey Fisher Island Field Station Miami, FL	H. Hudson E. Shinn
STATE AGENCIES	
Florida Bureau of Geology Tallahassee, FL	D. Curry A. Lewis
Florida Department of Community Affairs Tallahassee, FL	D. Heatwole
Florida Department of Environmental Regulation Office of Coastal Management Tallahassee, FL	K. Swanson
Florida Department of Environmental Regulation Marathon, FL	R. Hebling

Table A.1. (Continued).

Agency/Organization	Contact(s)
STATE AGENCIES (Continued)	
Florida Department of Natural Resources Marathon, FL	J. Hunt
Florida Department of Natural Resources Division of State Lands Tallahassee, FL	E. Hachenberger
Florida Department of Natural Resources Marine Research Laboratory St. Petersburg, FL	W. Jaap J. Kimmel
Florida Sea Grant Key West, FL	Librarian
South Florida Water Management District West Palm Beach, FL	S. Bellmund
State of Florida Office of the Governor Tallahassee, FL	P. Johnson D. Tucker
COUNTY AGENCIES	
Dade County Department of Environmental Resource Management Miami, FL	S. Markley
Monroe County Planning Department Marathon, FL	L. Castillo
Monroe County Industrial Development Authority Marathon, FL	B. White
ORGANIZATIONS/INDUSTRY/PRIVATE COMPANIES	
American Petroleum Institute Washington, DC	J. Gould
Gulf of Mexico Fishery Management Council Tampa, FL	T. Leary
Harbor Branch Oceanographic Institution Ft. Pierce, FL	G. Gilmore
Harbor Branch Oceanographic Institution Big Pine Key, FL	B. Lapointe
Island Navigator Big Pine Key, FL	S. Barrett
Mote Marine Laboratory Sarasota, FL	R. Heuter
National Audubon Society Research Center Tavernier, FL	S. Sprunt G. Powell
Union Exploration Partners, Ltd. Houston, TX	R. Oliver

* Does not include contacts made by chapter authors.

APPENDIX B

SPECIES PROFILES OF BIRDS

Oscar T. Owre

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INTRODUCTION

Profiles of bird species are presented in this appendix. Organization of coastal birds follows the American Ornithologists' Union (AOU) (1983) listing for orders and families; within families, species are considered in subgroups and are listed in alphabetical order by common name. For land birds, species are alphabetically arranged (by common name) within five categories (see **Chapter 9**). Someone seeking information about birds occurring within the study area should find within the individual profiles the basic information about each species. References included in the profiles can be consulted for additional information.

Species of the study area are summarized in the species profiles in terms of Occurrence in Study Area; Seasonality; Habitat/Natural History; Foraging (with emphasis on methods of foraging); Prey/Food; and Comments.

In the species profiles, I have not referenced long-held, commonly accepted knowledge about species. However, sources are cited for information that is recent, contrary to previously accepted information, controversial, or of outstanding interest. The standard references to South Florida birds that have been consulted are also listed in the References Cited section.

Coastal and offshore avifaunas have come under increasing scrutiny during the last two decades. To biologists, of course, the lack of information about these communities of birds has presented a challenge. To environmentalists, increasing ship traffic along the peninsula's coastlines arouses growing concern over the increasing oil pollution of marine waters and its effects upon the avifauna and all forms of marine life. Now, with offshore oil-prospecting being considered and with the possibility of functional wells on the continental shelf, need of information about the birds is pressing both for those who will be entrusted with safeguarding this natural resource as well as for those who will be concerned with appropriate industrial safeguards. What species are we concerned about? Where are they

found and when? What are their habits? What can be deduced as to their vulnerability to oil?

Knowledge is useless unless organized, and much of the information we have about coastal and offshore birds has lain scattered through a voluminous literature. Several summaries of knowledge regarding the coastal and offshore avifauna of southern Florida, pertinent to the study area, have recently been published. Field investigations have inventoried concentrations of coastal colonial birds, and information from stations and transects at sea has been published. Finally, aerial surveys have censused birds of areas of the coast and open sea.

Useful in preparation of this report have been a number of recent summaries of information. Full citations of these publications are given in the References Cited. Woolfenden and Schreiber (1973), both authors of long experience with Florida ornithology, presented much information in an early report about birds in saline habitats of the eastern Gulf of Mexico which remains pertinent to the study area. Gusey (1981) discussed birds in the Florida Keys, and certain species ranging into the Gulf of Mexico. Kale (1979a, b), a Florida ornithologist with a career of experience in the State, authored two reports on selected groups of birds on the Atlantic and Gulf coasts of Florida. Clapp et al. (1982a,b, 1983) presented voluminous reports on the marine birds of the southeastern U.S. and Gulf of Mexico. This is the most recent presentation of literature-search material. The bibliographies are extensive. Various aspects of oiling in birds and the problems of oil pollution are discussed at length.

Nesbitt et al. (1982) covered breeding sites for herons and their allies in coastal and interior areas of the peninsula and the Florida Keys. Portnoy et al. (1981) atlased gull and tern colonies as well as those of pelicans, cormorants, and skimmers from North Carolina to Key West and the Marquesas. Coastal waterbird colonies along Florida's entire coastline, the Keys, and the Dry Tortugas are covered by Spendelow and Patton (1988). Also included is data for northern populations of herons, gulls, and terns along the Great Lakes (an area of origin of some of our wintering species). Based on aerial surveys of outer continental shelf areas, Fritts et al. (1983) gave an overview of birds in the northern Gulf of Mexico and nearby Atlantic waters, as well as in an area southwest of Naples, Florida and extending into the Dry Tortugas area.

The list of birds that can be expected to occur within the study area is long. To list each species would be impractical. Marine and brackish-water oriented species have been given the most consideration. Most of the species of the littoral zone of marine and brackish habitats are carefully considered. All species in Categories of Concern recorded from the study area, whether from aquatic or terrestrial habitats, are included. A sample of the terrestrial migrants pausing in or flying through the study area is given. Finally, samples of land birds of several kinds of residences and points of interest are discussed. It should not be forgotten that marine-bordering terrestrial areas can be compromised by marine pollution.

In the species profile "Comments," the writer admits to degrees of subjectivity. It is not easy to anticipate parameters of an oil spill or other forms of oil pollution. One can only make broad guesses as to the effects upon the animals. Even more subjective are my comments regarding "why" any considerable mortality should not be acceptable. Nevertheless, as a biologist who has practiced for more than 30 years in South Florida, I believe such comments have a place in this manuscript.

Data Sources

Christmas Bird Counts (CBCs) have been utilized in providing information about winter abundances of species. Three such counts are available from the study area from:

(1) Everglades National Park (Coot Bay area). The area consists of lakes, bays, and Florida Bay (45%); coastal prairie (25%); mangrove swamp (15%); and tropical hardwood hammock (15%).

(2) Upper Keys (Key Largo to Plantation Key). The area consists of ocean and bay (50)%; hardwood hammock and residential (40%); ponds and swamps (5%); and flats (5%).

(3) Lower Keys (Big Pine Key area). This area consists of beaches, ocean, and Gulf (30%); tropical hammock (5%); saltwater ponds and mudflats (30%); mangrove swamps (20%); and pine-palm forest (15%).

In interpreting the data afforded by the counts, one should be aware that the numbers represent but three small areas from within a very large one; in short, they are only "samples" of the bird life taken at three different points. It will be readily seen that the Coot Bay-Everglades National Park data present greater species diversity as well as greater numbers of many species: this count area covers the peninsular edge as well as tidal-flat/sandy areas which have traditionally afforded foraging opportunities for diverse assemblages of birds. Each count has its compiler (name) usually cited when making reference to that count. Were this procedure to be observed, more than 30 compilers' names would be added to the References Cited. To restrict the number of citations, I have taken the liberty of citing only the Senior Editor for that issue of *American Birds*. My apologies to the compilers. I have not cited references with each use of CBCs. Editors are: Arbib, 1977 to 1983; Farrand, 1984 to 1985; Drennan 1986 to 1987. I have not refined CBC data to numbers seen/party hour; the totals seen are the important data for this report.

Terminology

A brief discussion of terminology is in order. Abbreviations used in the species profiles are noted below.

Seasonality

Basic to appreciation of the ecology of the study area's avifauna is consideration of the species' seasonality of occurrence. The following designations are widely used in describing seasonal occurrence (see, e.g., Wallace and Mahan 1975).

- Accidental Visitor (AV). Occurrence unexpected and not predictable. Caution must be used in applying this designation. With species whose ranges are poorly known, as is the case with many pelagic birds, this designation may not accurately portray the situation. Also, with respect to range changes, first records may be AV; later, as birds become more often in evidence, this designation may have to be changed.

- Casual Visitor (CV). Individuals or numbers of individuals of a species present only occasionally and often with irregularity.

- Migratory Visitor (MV). Species present only while passing through the study area in fall (about August to October) or spring (about March to May) or during both these periods.

- Permanent Resident (PR). Species present the year-round within a given locality. Only some part of a species' population may be permanently resident; that part usually breeds. Another portion of the population may be migratory. Example: many heron species have a permanently resident population within an area and breed there. Their numbers are augmented in winter by migrants from elsewhere but these migrants do not breed in the area.

- Summer Resident (SR). Species that are present only in summer; this is usually their reproductive season. This may not be the case with pelagic birds which breed in the Southern Hemisphere in "their" summer and spend "their winter" in the Northern Hemisphere summer.

- Winter Resident (WR). Present only in winter. Such birds usually do not breed in the area.

"Breeding season" is a term seasonally well-defined in the Temperate Zone. It is not as well defined in the subtropics and tropics, where some species may breed over considerable periods of time; often such extended breeding seasons will have one or more "pulses" of major breeding. Some water birds of the study area, e.g., the Double-crested Cormorant (*Phalacrocorax auritus*), can be found breeding in any month but there are times when major numbers breed.

Ecological Habitats

The study area's birds can also be grouped by their ecological habitats. Three major zones are recognized:

- Intertidal Zone. The area lying between mean low and high tides.

- Inshore Zone. From the lower edge of the intertidal zone to about 8 km (4.3 nmi) from shore.

- Offshore Zone. From about 8 km (4.3 nmi) offshore to the continental shelf edge (200 m). Found here are species that (1) return to land at night; and (2) enter the area from the pelagic zone and, except when breeding, are independent of land.

Major Categories of Foraging

It is well to appreciate, particularly from the standpoint of oil pollution, the many ways in which birds may be adapted to forage (see Ashmole 1971).

- Forage underwater (submerged) while swimming.

- Plunge from air into water--shallow plunging or deep plunging which is usually terminated by swimming.

- Forage while swimming on surface--reach to bottom for food; filter material from water with bill; scoop or pick food from surface.

- Forage from surface while in flight--skim surface with bill; pluck from surface.

- Forage while wading or walking.

- Mangrove foragers (not from intertidal zone waters)--forage from bark or twigs; glean from leaves; "flycatch" within and above canopy; forage above canopy while in rapid flight.
- Forage as predators or robbers (kleptoparasites) of other birds.
- Scavenge upon dead animals, refuse, etc.

PROFILES OF COASTAL BIRDS

A. Loons [Order Gaviiformes, Family Gaviidae]

Arctic Loon - *Gavia arctica*

There is one record of the Arctic Loon (*Gavia arctica*) from the Dry Tortugas (Kittleson 1976); this is apparently the only record from extreme South Florida.

Common Loon - *Gavia immer*

Occurrence in Study Area. WR. Florida Bay, large estuaries, inshore waters of exposed coastlines; the Dry Tortugas. According to Robertson and Mason (1965), "uncommon" offshore extreme southern Florida. Woolfenden and Schreiber (1973) commented that the species is almost impossible to census accurately (see below under Comments). CBCs, from three points within the study area, 1977 to 1987: average yearly total 7; maximum yearly total 18; minimum, 3.

Seasonality. October to May; peak numbers December to February.

Habitat/Natural History. Breeds on tundra and boreal freshwater lakes. Solitary in winter. Inhabits inshore waters of estuaries and bays. Known to range in the open Gulf as far as 140 km (75.5 nmi) offshore (Kale 1979b). Sleeps on the water. In February, loons undergo simultaneous molt of flight feathers and become temporarily flightless (Woolfenden 1967). According to McIntyre (1986), Minnesota-area loons winter along Gulf shores; central-Canada birds winter off the Atlantic coast. In the eastern Gulf of Mexico off Southwest Florida, Fritts et al. (1983) found Common Loons concentrated within 95 km of the coast.

Foraging. Submerges from surface. Pursues fish underwater and picks prey from bottom. Foot-propelled. Usual freshwater depths 4 to 10 m (Roberts 1932); depths to 70 m claimed (Schorger 1947).

Prey/Food. Fish up to 28 cm (Cramp et al. 1977); also crustaceans, molluscs, worms, etc.

Comments. Oil Vulnerability Index (OVI) among highest for birds, 47 to 65/100 (King and Sanger 1979). Loon numbers much reduced by breeding-habitat loss, by human interference on the breeding grounds, and by the thousands killed from undetermined causes offshore Florida (McIntyre 1986). Oil spills pose a serious threat to loon populations. Woolfenden and Schreiber (1973) commented that three days after a 1970 Tampa Bay oil spill, 70 Common Loons were obtained along the shorelines and that undoubtedly but a few of the sick loons were found; such numbers were never censused there before. Even small numbers of loons, were they to be affected in the study area, are important to those of the North who regard these birds as "tangible evidence of wilderness" (McIntyre 1986).

Red-throated Loon - *Gavia stellata*

The Red-throated loon (*Gavia stellata*) is a CV to the Gulf of Mexico where it is uncommon (Clapp et al. 1982a). It is rarely seen in extreme South Florida. CBCs, from three points within the study area, 1977 to 1987, recorded a total of only 3 individuals on two separate occasions.

B. Grebes [Order Podicipediformes, Family Podicipedidae]

Eared Grebe - *Podiceps nigricollis*

Rare in winter; primarily coastal.

Horned Grebe - *Podiceps auritus*

Occurrence in Study Area. WR. Present in so-called "lakes" of deeper water within Florida Bay (A. Sprunt IV, pers. comm. 1989, National Audubon Society). CBCs, 1977 to 1987, from three points in the study area: average yearly total 55; maximum yearly total 103; minimum, 20.

Seasonality. October to April.

Habitat/Natural History. Breeds circumpolarly in inland waters in North America south to northern states. Winters coastwise, mainly in sheltered bays, inlets, and shallow inshore waters. Frequents rough water more than other small grebes; buoyant in waves.

Foraging. Sinks or dives from surface. Foot-propelled. Usual depths to 25 m (Cramp et al. 1977). Usually solitary, but reported to congregate at schools of fish.

Prey/Food. Diet shifts with prey availability. According to Cramp et al. (1977), arthropods, especially insects and their larvae, and fish.

Comments. Highly susceptible to oil.

Least Grebe - *Tachybaptus dominicus*

This grebe is resident in South and Central America to Texas and in the Greater Antilles and the Bahamas. It is largely a freshwater inhabitant. There are three possible records from extreme South Florida and one probable record (see Robertson 1971).

Pied-billed Grebe - *Podilymbus podiceps*

Occurrence in Study Area. PR, WR. In winter, numerous in freshwater habitats inland of coastal rim; to some extent in mangroves and sheltered coastal areas. Many of these are migrants from the north. To what extent in winter the freshwater nesting population of South Florida moves into the coastal habitat is not known. CBCs, 1977 to 1987, from three points in the study area: average yearly total 48; maximum yearly total 165; minimum, 4.

Seasonality. Migration pulses: September to November; March to May. Inland breeding dependent upon high water and thus irregular, largely July to November.

Habitat/Natural History. Breeding population in interior wetlands; nests, floating masses of aquatic weeds amongst emergent vegetation. Grebes stay close to shore; usually sleep on the water. Known, infrequently, to "crawl" onto lily pads or marshy shores to sun (Bent 1919).

Foraging. Dives or sinks from surface; pursues prey under water. Foot-propelled. Depths usually to about 6 m (Cramp et al. 1977).

Prey/Food. Crustaceans, aquatic insects, other small invertebrates, and small fish.

Comments. Grebes are very susceptible to oil; OVI is 44 to 56/100 (King and Sanger 1979). Of particular concern: oil spill that involves mangrove shorelines and inland brackish waters.

Red-necked Grebe - *Podiceps grisegena*

Rare in winter; recorded off Tavernier, Key Largo (Sprunt 1963).

Western Grebe - *Aechmophorus occidentalis*

AV, Gulf coast.

C. Pelicans and Allies [Order Pelecaniformes]

1. Pelicans [Family Pelecanidae]

American White Pelican - *Pelecanus erythrorhynchos*

Occurrence in Study Area. WR; a few, non-breeding, remain in summer. Principally close offshore the Cape Sable area as well as at inland lakes. CBCs, 1977 to 1987, Coot Bay-Everglades National Park and Key Largo areas: average yearly total 1,493; maximum yearly total 4,024; minimum, 619. Other CBC points in study area, inconsequential numbers.

Seasonality. Fall arrivals October; most gone by May.

Habitat/Natural History. Frequents bays, estuaries, mangrove shorelines, and inland brackish/freshwater areas. Chapman and Loftus (1986) reported that the White Pelican utilizes freshwater marshes in Everglades National Park. They found the birds present at marsh-mangrove interfaces in Shark Valley. Loaf and roost on sandspits and exposed tidal flats. Breeds in the northwest and north-central parts of the continent, sporadically to the Texas coast.

Foraging. While swimming. Submerge head and scoop fish into gular sac. Also forage cooperatively, swimming in line abreast to herd fish.

Prey/Food. Almost exclusively fish.

Comments. Vulnerable to plumage-oiling while foraging and probably during much of its existence since it is never far from water, roosting near or on it. Vulnerable to ingestion of oil while scooping fish.

The Florida Bay population was over 5,000 in 1976 (Kushlan 1978b). Sidle et al. (1985) censused the North American population from 1979 to 1981 and totaled 109,000 birds, 41% being in the U.S. and the rest in Canada. Within Florida Bay, oil spills drifting into the coastal mangrove fringe might well imperil a significant part of the country's population as well as an additional population from Canada.

Brown Pelican - *Pelecanus occidentalis*
Florida Species of Special Concern (FGFWFC 1989)

Occurrence in Study Area. PR, WR. Wintering population a composite one. Post-breeding movements bring South Carolina-raised birds to Florida east coast, and along with birds raised on Florida east coast, these winter here and along the Upper Keys; Tampa Bay-raised birds move to upper Florida Bay (Flamingo), the Keys west of Marathon to the Dry Tortugas (Schreiber 1976). CBCs, 1977 to 1987, from three points within study area: average yearly total 1,324; maximum yearly total 2,266; minimum, 1,024 (1986). Breeds on mangrove islets in Florida Bay and (Schreiber and Robertson 1975) at Dry Tortugas.

Seasonality. Recorded breeding every month. Peak laying usually March to April. Dates for shifting of populations not exactly determined.

Habitat/Natural History. Frequents bays, estuaries, mangrove lakes, and mangrove fringes; inland brackish/freshwater areas to much lesser extent. Only occasionally seen offshore zone at 32 to 64 km (17 to 34.5 nmi), rarely further (Schreiber 1978a). Roost and nest in coastal mangroves; also roost on sandspits and bars offshore. Gregarious. Nests on mangrove islets. Nests a platform of sticks atop branches; grasses and debris heaped on sticks. Eggs, 2 to 3; incubation, 28 to 30 d; time to fledging, 11 to 12 wk (Schreiber 1978a). Colonial in nesting, often with other species.

Foraging. Plunge-dive, much of plumage potentially submerged.

Prey/Food. Almost entirely fish. Frequents fish-cleaning stands for refuse.

Comments. Highly vulnerable to plumage-oiling while swimming and "plunge-diving." Pollution that affected fish populations would certainly affect the Brown Pelican populations. The extended period of dependence of the young and their deferred maturity accentuates the threat of any unnatural mortality of the populations. Schreiber (1978a) stressed the importance of maintaining integrity of South Florida populations in light of the species' scarcity in states where formerly abundant. It should be noted that from monthly censuses, 1977 to 1981, Kushlan and Frohring (1985) calculated a 40% drop in Florida Bay populations.

2. Cormorants [Family Phalacrocoracidae]

Double-crested Cormorant - *Phalacrocorax auritus*

Occurrence in Study Area. PR, WR. At all times of the year, a very common bird, probably most common swimming avian piscivore of the study area. Breeds colonially in fringing mangroves and mangrove islets. In winter, numbers much augmented by migrants from the north, of a different subspecies, *P. a. auritus*. Local PRs, *P. a. floridanus*. CBCs, from three points within the study area, 1977 to 1987: average yearly total 2,992; maximum yearly total 4,102; minimum 1,625.

Seasonality. In Biscayne Bay, Cummings (1987) reported average counts of 1,300 during April to August, and 3,500 between November to February. A similar increase should occur in Florida Bay immediately to the south. At this southern point in the species' breeding range, nesting recorded for all months (Portnoy et al. 1981), and there may be more than one annual peak of nesting. McEwan and Kushlan (1977) reported nest increases October to December, from 200 to 800 in South Florida national parks (most nests in the study area). Bass and McEwan (1978) found nesting January to March, with a peak of 1,100 in March. Cummings (1987) reported April to August as peak breeding in Biscayne Bay.

Habitat/Natural History. This cormorant is found in relatively open water in the interior freshwater wetlands. The largest concentrations are in protected coastal waters (e.g., bays, estuaries, and to leeward of islets). Also range beyond inshore waters to points far offshore. Kale (1979b) cites offshore distances in the Gulf of 37, 74, and 82 km (20, 40, and 44 nmi).

Nesting in Florida Bay recorded from numerous Keys (i.e., Arsnickers, Buchanan, Channel, Cuthbert, Frank, Green Mangrove, and Sandy). Nests usually in mangroves; of sticks and lined with seaweed/grasses. Eggs, 2 to 6; incubation, about 25 d; first flights to water from which then take off (about 42 d); accompany adults until about 10 wk when become independent (Terres 1980). Colonial in nesting, often with other waterbird species.

Much time spent afloat, preening and sunning, often in loose congregations. Also sun and preen in groups on bars and sandy beaches. Perch on buoys, channel markers, pilings, sailboats, etc. Roost at night in mangroves, usually on islets.

Foraging. Land on water from flight. Dive from surface. While submerged, pursue prey or hunt the bottom. Swim with feet. Usual depths 1.5 to 7.5 m (Terres 1980). Some areas of plumage become water-soaked (Owre 1967). Howell (1932) described several thousand cormorants following a "run" of fish.

Prey/Food. Almost exclusively fish; some crabs, shrimp, and other crustaceans taken. Cummings (1987) listed fish from samples of food fed to young. Apparent order of food preference: gulf toadfish (*Opsanus beta*), bluestriped grunt (*Haemulon sciurus*), bucktooth parrotfish (*Sparisoma radians*), white grunt (*Haemulon plumieri*), and pinfish (*Lagodon rhomboides*). *Opsanus beta* (toadfish) constituted 40% by weight of food fed young.

Comments. OVI for this family, 52 to 63/100 (King and Sanger 1979). High OVI results from: (1) foraging while submerged; (2) much time afloat preening, etc.; (3) long, running take-offs; and (4) loosely gregarious in foraging, etc. Probably not taken into previous account for OVI: (1) hazard to eggs and young from plumage of oiled adults; (2) possibility of nest construction materials (seaweed, trash) gathered from water being oiled and this transferred to eggs or young; (3) first flights of young are to water; and (4) potential of oiled fish being fed to young during the long period spent in the nest and during the long period of dependence on parents. *Not* previously taken into account for high OVI: southern Florida has the highest winter density of these cormorants in the U.S. (Root 1988); cormorants from a large part of the U.S. winter in the study area and widespread mortality at this time will affect populations from other portions of the continent.

In terms of the ecological importance of this bird, Cummings' (1987) data are important. She calculated that in Biscayne Bay, the cormorants take 271,000 kg of fish/yr and return to the bay 26,000 kg of guano/yr. Clearly, these birds are an integral part of the ecology of this and other subtropical estuaries.

Finally, W. B. Robertson (pers. comm. 1989, biologist, U.S. National Park Service) witnessed complete disappearance of these birds from the Dry Tortugas Atoll when oil from a 1964 spill drifted into that area. A census of the cormorant population shortly before arrival of the oil recorded 50 cormorants present (Robertson and Mason 1965).

Great Cormorant - *Phalacrocorax carbo*

Another species of cormorant, the Great Cormorant (*P. carbo*) is a very casual WV to southern Florida. Only a very few individuals have been reported from the area included in this study.

3. Anhingas [Family Anhingidae]

Anhinga (Water Turkey) - *Anhinga anhinga*

Occurrence in Study Area. PR, WR. Breeds in the wading bird colonies of Florida Bay, the mangroves along the mainland, and the freshwater wetlands. Forages within mangrove areas, but in much smaller numbers than in the freshwater wetlands. CBCs, from three points in the study area, 1977 to 1987: average yearly total 35; maximum yearly total 74; minimum, 14. All but six of these birds were from Coot Bay-Everglades National Park.

Seasonality. Migrants from the north arrive October to November; numbers decrease March to April. To what extent PRs shift about, not known. Nesting recorded in southern Florida for all months; peak of nesting December to April.

Habitat/Natural History. Although principally freshwater inhabitants, Anhingas are found in mangrove areas (Owre 1967; Burger et al. 1978) where they forage, roost, and breed. Birds require emergent vegetation (shrubs, trees) upon which to climb from water. Nests are in forks of bushes or trees and are of twigs, lined, and festooned with branchlets with green leaves. Eggs, 3 to 6; incubation, about 28 d. Young become ambulatory in nesting tree and, if disturbed, plunge into water; ability to regain tree questionable.

Foraging. While swimming submerged. Plunge from overhanging branches, or dive or sink from the surface. While submerged, move slowly and because of "wettability" of plumage, able to neutralize buoyancy (Owre 1967). Grasp small prey between mandibles, impale large prey; rise to the surface to ingest. At surface, swim low in the water, usually only neck and head emergent.

Prey/Food. Almost exclusively fish; some invertebrates.

Comments. Although relatively few birds are found in marine areas, concern for Anhingas results from the following considerations: (1) the birds plunge into the water and forage submerged; (2) their plumage is adapted to become water-soaked; (3) when swimming at surface, most of body submerged; (4) *all* of food gained while in water; (5) species not as abundant as formerly, largely disappeared in Texas (Oberholser 1974), declining rapidly in Arkansas (James and Neal 1986), and reduced in numbers and habitat in Florida (Owre unpubl. data); and (6) this is an unusual water bird, strikingly out of the ordinary in appearance. Few birds can have as high an oil vulnerability.

4. Frigatebirds [Family Fregatidae]

Magnificent Frigatebird (Man-O'-War Bird) - *Fregata magnificens*

Occurrence in Study Area. PR. Throughout the entire area, including inshore and offshore waters. At the Dry Tortugas (Harrington et al. 1972), counts from April to July gave a daily maximum number of 140, a minimum of 48. CBCs, 1977 to 1987, from three points in the study area: average yearly total 76; maximum yearly total 250; minimum, 14. Breeds irregularly, the localities varying.

Seasonality. Breeding March to ?. In Florida, less common when breeding at Bahamian and West Indian sites (Palmer 1962); most common in spring and summer.

Habitat/Natural History. Nesting in Florida first recorded at Marquesas Keys, 1969 to 1975 (Robertson 1978a); this colony presently not active. Now nesting, 1988 to 1989 at Loggerhead Key in the Dry Tortugas (W. B. Robertson, pers. comm. 1989). Nest flat-topped, loose platform of twigs lined with seaweeds and grasses. One egg; incubation, about 40 d; age at first flight more than 20 wk. Return to nest to be fed by adults. Gregarious. Females have heavier wing-loading than males. Bathe and drink in freshwater.

Foraging. Dependent upon wind for extensive flight (Robertson 1978a). Pick up prey from the sea surface and from the air (flying fish). Harass terns, boobies, other seabirds for food they are carrying. Take eggs and young from seabird colonies. Follow fishing boats for refuse. Progress over water by soaring aloft in thermals, then gliding. Fly over large expanses of water when foraging (Harrington et al. 1972).

Prey/Food. Fish, squids, refuse, eggs and downy young of seabirds, etc.

Comments. Vulnerability of this large seabird in an oil-contaminated environment difficult to assess. It does not land on water. Its food is from the ocean. It lines its nests with seaweed which could be oil-contaminated. A serious consideration is that it would feed on organisms weakened by oil. Mortality of the birds would be unfortunate, for as Robertson (1978a) wrote "its key value is aesthetic...it gives summer skies of southern Florida coasts an unmistakable tropical character."

D. Herons and Allies (wading birds) [Order Ciconiiformes]

1. Bitterns, Egrets, and Herons [Family Ardeidae]

a. Bitterns

Least Bittern - *Ixobrychus exilis*

Occurrence in Study Area. SR, WR. Bowman and Bancroft (1989) reported the first nestings in Florida Bay, these on mangrove islets. Abundance of this inconspicuous bird in the study area is not known. Whether or not this nesting population is present throughout the year is unknown. To what extent migrants pass through the area en route to wintering areas to the south is unknown. It is likely that a wintering population is made up from the nesting one and from more northern ones that migrate to South Florida.

Seasonality. Bowman and Bancroft (1989) reported nestings on 15 June 1988 (this nest with two fledged young on 5 July), 29 May 1987, and 12 June 1987 (two ambulatory young from this nest on 1 July).

Habitat/Natural History. Characteristic of dense, emergent aquatic vegetation with some wood, growth...brackish and saline swamps are used in winter (Hancock and Kushlan 1984). Bowman and Bancroft (1989) found nests in black mangroves of the Keys' central lagoons. Mangrove swamps may be used in winter (Bowman and Bancroft 1989). Nesting is usually solitary; however, Kushlan (1973) reported colonial nesting in freshwater marshes.

Foraging. According to Hancock and Kushlan (1984), foraging is characterized by walking slowly and stalking among leaves and branches or on branches over water. The birds may "stand in place" and engage in "neck swaying." After a strike, the birds usually shift foraging places. Individuals walk in crouched positions, neck extended, the bill nearly touching the water, and strike rapidly from this position.

Prey/Food. Small fish, insects, and many small aquatic animals.

Comments. This is a heron of the lower story of the marsh; it is seldom far from water. A wash of oil into the Bay's mangrove-covered islets could be serious for breeding and wintering populations. The sizes of these populations are not known. Important to gauge would be the threat of oil pollution to the population of the breeding birds.

b. Egrets

Cattle Egret - *Bubulcus ibis*

Occurrence in Study Area. PR, MV. Breeds in colonial water birds' nesting sites. CBCs, from three points in the study area, 1977 to 1987: average yearly total 131; maximum yearly total 364; minimum, 68.

Seasonality. Present in varying numbers throughout the year. In spring and fall, birds apparently in migration move along the Keys, and arrive and depart in flocks seemingly directionally oriented towards both Cuba and the Yucatan Peninsula. Breeds April to July.

Foraging. Principally in inland agricultural lands.

Prey/Food. Grasshoppers, crickets, spiders, small lizards, etc.

Comments. Native to the Old World. Early in the century, the species introduced itself to South America and spread north into the West Indies (Arendt 1988). First breeding record for Florida 1953. Approximately 20 years later, the second most common wading bird breeding in southern Florida (next to the White Ibis in numbers). 33,300 were recorded in the 1974 to 1975 breeding season (Kushlan and White 1975). Today the rookeries of nesting wading birds in Florida Bay, as well as in the interior wetlands, are in many cases dominated by Cattle Egrets. Unlike other species of wading birds present, Cattle Egrets' flights to foraging grounds are not to marine *or* freshwater areas, but rather to pastures, agricultural areas, and even urban grasslands. Here, it feeds largely on insects (e.g., grasshoppers, crickets, and spiders). Of all the wading birds in the study area, it is least likely to become oiled or suffer prey reduction from oiled foraging grounds. Degradation of its mangrove nesting sites throughout Florida Bay would presumably have an effect on the fertility of the Bay's waters; for this species, feeding on produce of terrestrial ecosystems, returns much of this (the nitrates, phosphates, etc.) to the waters about its nesting sites in the form of guano which enters the nutrient cycles of the Bay.

Great Egret - *Casmerodius albus*
(=American Egret, Common Egret, Great White Egret)

Occurrence in Study Area. PR, WR, MV. Two populations are present. The nesting one that may be more or less sedentary, the juveniles presumably dispersing elsewhere. According to Byrd (1978), migrants from the coastal Atlantic states and from about Ohio move to Florida in the fall; how many of these pass southward beyond Florida to winter is not clear. The egrets are present in the study area throughout the year. There is, no doubt, considerable movement between marine environments and the freshwater areas of the interior. CBCs, 1982 to 1987, from three points in the study area: average yearly total 1,800; maximum yearly total 3,524; minimum, 535. Of above CBCs, Coot Bay-Everglades National Park average yearly total 1,236; maximum yearly total 3,305; minimum, 399.

Seasonality. Nesting occurs year-round, its peak is February to April (Kushlan and White 1977a). According to Powell (1987), water levels in eastern portions of Florida Bay are too high for foraging from September into December, and birds at this time must fly long distances to forage or move elsewhere.

Habitat/Natural History. This is "a bird of wet habitats of all sorts" (Hancock and Kushlan 1984). Great Egrets utilize all wetlands, in which by virtue of its size the birds can forage, as well as dry coastal prairie adjacent to Florida Bay. Nesting, by single pairs or colonial. Nests in mangroves, other trees, bushes, etc. Nests, of sticks; eggs, 2 to 5; incubation, 25 d; young clamber from nest at 3 wk; fledge in three more weeks. Roosts in mangroves and other trees.

Foraging. In Florida Bay, foraging dependent on tidal levels. Powell (1987) describes the egret as a "medium species" in foraging depth (to a maximum of 28 cm). Forages solitarily and in groups. "Walking slowly" in water or on dry land comprises 60 to 90% of foraging time (Rodgers 1983). "Standing" is commonly used. When alone, usually defends area around itself. When feeding in groups, often "robs."

Prey/Food. Fish largest component of diet. Along shorelines, feeds on insects, amphibians, invertebrates, etc. On dry land, often takes small mammals.

Comments. Loss of wetland habitats everywhere and its general population decline across the U.S. (Wiese 1978) suggest that any unusual mortality of the species would be serious.

Little Blue Heron - *Egretta caerulea*
Florida Species of Special Concern (FGFWFC 1989)

Occurrence in Study Area. PR, WR, MV. Breeds in Florida Bay and mangrove-fringed coastline of the study area. Migrants pass through the area en route south; to what extent these linger or constitute a wintering population is not known. The numbers remaining in east Florida Bay must be small from September into December; for at this time, water levels make foraging for this species difficult (Powell 1987). CBCs, from three points in the study area, 1977 to 1987: average yearly total 817; maximum yearly total 1,546; minimum, 433.

Seasonality. Nests December to June (Terres 1980). Northern birds pass into southern Florida from October to November.

Habitat/Natural History. Shallow water for foraging, preferentially shallow water of freshwater marshes and grasslands. Nesting individuals from coastal colonies tend to fly inland to forage. Nesting and roosting trees include mangroves. Nest, of sticks, flimsy; eggs, 2 to 5; incubation, 21 to 25 d; young ambulatory 13 d; time to fledging?

Foraging. Leg-length categorizes it as a "small species" regarding maximum foraging depth (Powell 1987). Greatly influenced in marine environments by tidal ranges (Rodgers 1978). In eastern Florida Bay, from September through December, deep water is at a maximum and the smaller wading birds must either feed along island shores, the main Keys, leave the area, or shift to the western side of the Bay; foraging numbers on the Gulf side of the Bay are very large from October into November and at other times of the year. Kushlan (1978a) described the species as being among the most versatile regarding feeding-behavior patterns. Commonest feeding behavior is "walking slowly" through shallow waters. Diurnal.

Prey/Food. Mostly slow-swimming fish or substrate-crawling invertebrates; prey types in conformity with usual foraging behavior (Rodgers 1982).

Comments. Probably not critical regarding vulnerability to oil spills in marine environment since it forages to large extent in fresh water.

Reddish Egret - *Egretta rufescens* (formerly *Dichromanassa rufescens*)
Florida Species of Special Concern, USFWS Under Review 2 (FGFWFC 1989)

Occurrence in Study Area. PR. The population is largely sedentary. Found throughout Florida Bay and along the Lower Keys. Rare inland. Extralimital populations exist along the Gulf coast of Texas, Mexico, and locally in the West Indies. CBCs, 1982 to 1987, from three points in the study area: average yearly total 89; maximum yearly total 144; minimum, 60.

Powell et al. (1989) summarized knowledge of the historical and current status of the Reddish Egret in Florida Bay. Early in the century, the species appears to have been extirpated not only from the Bay but from the entire State. After exploitation of the herons became unlawful, the egrets were recorded again in 1937 (probably recolonizing from outside the State, presumably from the western Gulf coast where they were still present). In the 1970's, the population was estimated at about 300 birds (Robertson 1978e). The population has not been surveyed since 1980. Presumably the scarcity of fish, as is now evident throughout the Bay, is affecting its breeding success.

Seasonality. Nests almost year-round, with peaks November to January and February to May.

Habitat/Natural History. "Brackish marshes and shallow coastal habitats, breeding in low trees primarily in red mangroves" (AOU 1983). Nests individually or in small groups. Nest, of twigs; eggs, 3 to 4; incubation, 26 d; after 6.5 wk, young make short flights.

Foraging. Marine flats and shorelines. Maximum foraging depth about 26 cm, or a "medium species" in foraging-depth potential (Powell 1987). Foraging methods exceedingly variable and include such as "walking quickly," "running," "hopping," "wing-flicking," and "double-wing feeding" (Kushlan 1978a). It runs in a semi-crouch across the marine flats, frequently flicking its wings. One of the most active herons.

Prey/Food. Mostly small fish.

Comments. The Florida Bay population is probably a unique one in terms of its gene pool. Its numbers are estimated below 300 pairs (Hancock and Kushlan 1984). Any unnatural mortality would be extremely serious in a population ecologically restricted to an area in which the productivity of its food sources has become submarginal.

Snowy Egret - *Egretta thula*
Florida Species of Special Concern (FGFWFC 1989)

Occurrence in Study Area. PR, WR, MV. Coastal areas of mainland and Keys to the Marquesas and Dry Tortugas. Nests in Florida Bay islets, coastal mangrove areas, and freshwater wetlands inland. Florida breeding birds believed largely sedentary, although some to Panama in winter (Hancock and Kushlan 1984). Mid-Atlantic states' birds migrate through the study area en route to and from South America. CBCs, from three points in the study area, 1977 to 1987: average yearly total 1,446; maximum yearly total 2,932; minimum, 405.

Seasonality. Nesting dependent upon hydroperiod, usually March to August. Fall migrants, October to November.

Habitat/Natural History. Less restricted to coastal areas than Tricolored Heron (Hancock and Kushlan 1984). Largest nesting colonies usually in coastal estuarine areas (Ogden 1978e). Nest, of twigs; flimsy; in trees (often mangroves, bushes, etc.). Eggs, 3 to 4; incubation time and fledging time, ?. Large communal roosts when not breeding.

Foraging. Diurnal. In flocks. Very active in pursuit of prey. Repertoire of foraging behaviors most diverse of herons studied (Hancock and Kushlan 1984): primarily "walking slowly," "standing," and "walking quickly"; specializes in foot movements to attract fish, as well as aerial methods of attraction. Frequents pastures and other dry ground at times.

Prey/Food. Varied. Insects (particularly grasshoppers), cutworms, small fish, lizards, small snakes, etc.

Comments. Because it frequents freshwater habitats in considerable part, it is somewhat removed from the hazards of contaminated marine environments.

Tricolored Heron (=Louisiana Heron) - *Egretta tricolor*
Florida Species of Special Concern (FGFWFC 1989)

Occurrence in Study Area. PR, WR, MV. Northern U.S. birds pass through the study area to and from the West Indies and South America. Local breeding birds sedentary? Post-breeding dispersal. Found throughout the study area. CBCs, from three points within the study area, 1977 to 1987: average yearly total 723; maximum yearly total 1,582; minimum, 185.

Seasonality. Breeds February to July. Northward migration from south, February to March.

Habitat/Natural History. Most common in estuarine habitats, shallow coastal marshes and in bays. Nests in trees standing in water, often mangroves. In mixed colonies throughout Florida Bay; also freshwater wetlands. Nest of sticks, usually <3 m above ground. Eggs, 3 to 4; incubation, 21 d; young clamber from nest after 3 wk; fledge about 5 wk.

Foraging. Shallow aquatic habitats, often mudflats. Varied foraging methods, often "flicking" wings (see Hancock and Kushlan 1984).

Prey/Food. Primarily fish, crustaceans, and aquatic insects; also snails, amphibians, etc.

Comments. Because of its greater preference for estuarine and coastal areas (Ogden 1978f), more vulnerable to oil than many of the smaller herons.

c. Herons

Black-crowned Night-Heron - *Nycticorax nycticorax*

Occurrence in Study Area. PR, WR, MV. Present year-round in Florida Bay and southwest coastal areas. Uncommon in Florida Keys. A breeding population-(sedentary?), wintering birds from elsewhere and a large population of migrants en route to and from probably Cuba and other areas beyond Florida (Byrd 1978) are present. Note: in Monroe County, only two of 44 nesting rookeries listed by Nesbitt et al. (1982) contained this species; on the other hand, the birds are not always easy to count and may nest solitarily. CBCs, from three points within the study area (with birds only recorded from the Coot Bay-Everglades National Park area), 1977 to 1987: average yearly total 27; maximum yearly total 61; minimum, 2.

Seasonality. Breeding season largely December to May or later. Build-up of migrants begins early fall.

Habitat/Natural History. "Virtually all types of shallow water areas suitable for feeding" (Dunstan 1978a). In Florida, concentrates about estuaries. Common in mangroves and other trees where they forage, roost, and nest. Nest singly, in groups, and in colonies of mixed species. Nest, of twigs; flimsy; in mangroves and other growth. Eggs, 3 to 5; incubation, 21 to 22 d; 6 wk to fledging, but clamber from nest at 3 wk.

Foraging. Typically at night or crepuscularly; also diurnally when, however, subject to attack by day herons (Hancock and Kushlan 1984). Forages solitarily and maintains territory, or forages in groups. "Standing" and "walking slowly" common foraging behaviors; also reported are "hovering," "diving," and "swimming feeding." The writer has watched this bird dive into water from low overhanging branches.

Prey/Food. Mostly fish and other aquatic organisms, but diet very diverse. Apparently a well-known predator of eggs and young of other aquatic birds (Hancock and Kushlan 1984). Also known to scavenge dead fish.

Comments. Abundance in the study area not surely known since the birds are secretive, roost in dense cover, and forage at night. How would nocturnal feeders react to a drift of oil into the mangroves?

Great Blue Heron (blue color morph) - *Ardea herodias*
("Wurdemann's Heron" is a white-blue color morph cross)

Occurrence in Study Area. PR, WR. This color morph is found throughout coastal and estuarine areas. Population structure is complex (Powell 1987). An apparently largely sedentary population breeds here; in winter, a migratory component of northern populations is present. CBCs, 1982 to 1987, from three points in the study area: average yearly total 338; maximum yearly total 404; minimum, 281.

Seasonality. Migrants arrive October and November (Powell 1987); these gradually leave during late winter and spring (February to April). The blue and white morphs breed simultaneously. The majority of nests are found from September to February (Powell 1983), but some nesting birds are found throughout the year.

Habitat/Natural History. Coastwise and estuarine (freshwater wetlands as well). Nests on mangrove islets in Florida Bay and on offshore Keys to Key West and the Marquesas Keys. Nests solitarily or in colonies. There is rare interbreeding of color morphs. Some idea of relative sizes of breeding populations of the two morphs can be gained by comparing total nests of each, counted during the three-year period 1976 to 1978: 274 white morph nests and 142 blue morph nests were tabulated within Monroe County portions of the study area (Nesbitt et al. 1982). Nests, eggs, incubation, etc., as white morph.

Foraging. Coastwise, on tidal flats, along tidal passes, on the mudbanks that characterize Florida Bay. Uncommonly on open, dry ground. Maximum foraging depth about 39 cm. Foraging methods principally "stand and wait" and "walk slowly." Krebs (1974) described "hover catching," "swimming and striking at prey under water," and "hover and swoop." Solitary and territorial to social feeding in flocks of as many as 50. According to Krebs (1974), a "partly social" forager, its social feeding increasing as does the "richness of prey." Forages throughout the diel cycle; moonless nights no deterrent (Black and Collopy 1982).

Prey/Food. Mostly fish, probably much the same species as the white morph. A wide variety of invertebrates taken as well as amphibians, small birds and mammals (Krebs 1974), and dead fish floating and on the shoreline.

Comments. Concerns for this heron are several: (1) The resident population appears sedentary and its location at the end of the peninsula suggests a gene pool different from other continental populations and adapted to subtropical conditions. Any considerable mortality within any such unique population is to be avoided; (2) A relatively dense population is found in winter around Cape Sable (Root 1988). This population represents, in part, populations from elsewhere. Mortality in the wintering population could affect local breeding populations from other parts of Florida and/or the U.S.; (3) Depths at which the birds can forage and their scavenging of dead fish suggest potential for oiling and sublethal effects from ingesting oil-killed prey. Nothing is known of the herons' reactions to oil by day, let alone by night; and (4) Long incubation period and long period before fledging (6 to 8 wk) increase danger of exposure to possible oil spill.

Great Blue Heron (white color morph) - *Ardea herodias*
(formerly Great White Heron - *Ardea occidentalis*)

Occurrence in Study Area. The major range and virtually the entire nesting area of the white morph (Florida Bay and the Lower Keys) lie within the study area. Largely sedentary, but a few immatures disperse regularly to the Dry Tortugas and into the Florida peninsula (Robertson 1978b). CBCs, 1982 to 1987, from three points in the study area: average yearly total 316; maximum yearly total 466; minimum, 271.

Powell et al. (1989) reviewed historical and current status of this color morph to date. During the latter 1960s, the population comprised about 900 birds. In 1984, a survey indicated a similarly sized population. Powell's studies have indicated a lack of reproductive success of this color morph, apparently due to inadequate food supplies.

Seasonality. Breeds during any month, but the majority of nests are September to February (Powell 1983).

Habitat/Natural History. Coastal and estuarine. Nests on mangrove islets in Florida Bay and westward along offshore Keys (Great White Heron National Wildlife Refuge) to Key West and the Marquesas Keys. About half of the islands in East Florida Bay are used as breeding sites for one to 50 pairs; some have blue morph individuals mixed in. Nests principally on black mangroves but other trees also utilized (Powell 1983). Nest, of sticks; 1-m diameter. Eggs, 3 to 7; incubation, 28 d; successful nests fledge 2 to 3 young in about 2 mo.

Foraging. Coastwise, tidal flats and the interlacing mud banks within Florida Bay. Rarely on dry shoreside prairies (Robertson 1978b). Maximum foraging depth about 39 cm. Foraging methods principally "stand and wait" and "walk slowly." In East Florida Bay "may feed at anytime, day or night; because of size, is independent of water levels year-round" (Powell 1987). In East Florida Bay, forages principally at night (Powell 1983).

Prey/Food. Fish (up to 30 cm in length); also shrimp and other crustaceans (Robertson 1978b).

Comments. Concerns for this heron are several: (1) the range of this morph is largely restricted to Florida Bay and the Keys to the west; any considerable mortality there could jeopardize the population which is not large; (2) food availability has become a factor in limiting clutch size and fledging success (Powell 1983). The population, therefore, is now apparently stressed; (3) there is a long time to maturity, with an incubation period of 30 d and with the young in the nest for 6 to 8 wk; and (4) this stately, large bird is a major aesthetic feature of South Florida estuaries (Robertson 1978b).

Green-backed Heron - *Butorides striatus*

Occurrence in Study Area. PR, MV. Breeding population present more or less throughout the year. Juveniles presumably disperse widely. A large migrant population passes through southern Florida to the Bahamas and other Caribbean islands. To what extent these linger or remain throughout the winter is not clear. CBCs, from three points within the study area, 1977 to 1987: average yearly total 111; maximum yearly total 184; minimum, 18.

Seasonality. Peak of the nesting season, March to May. Nesting is less dependent upon seasonal water levels than many ardeids since the birds rarely wade but forage from emergent trees, bushes, etc. and from shorelines, and are not as dependent upon tidal conditions. Migrants arrive October to November.

Habitat/Natural History. Found along "forested water margins" (Hancock and Kushlan 1984) of freshwater and marine ecosystems. In the study area, it is found virtually everywhere there are stands of mangroves. The birds nest singly, in small groups, or in mixed-species colonies. Nests, of twigs, in bushes and trees. Eggs, 2 to 4; incubation, 21 to 25 d; young climb when 1 wk old; fledge 5 wk.

Foraging. Feeds by night and day. Most frequent foraging behaviors: "standing in crouched position" on branch or shore and "walking slowly" (Hancock and Kushlan 1984). Other behaviors are "plunging," "jumping," and "swimming feeding." Solitary and highly territorial.

Prey/Food. Mostly small fish and insects.

Comments. Dark-plumaged, secretive small herons are difficult to census. Extent of the population not known. Vulnerability of the population to oiling does not appear a serious consideration.

Yellow-crowned Night-Heron - *Nycticorax violaceus*

Occurrence in Study Area. PR, WR, MV. Breeds widely where appropriate foraging and trees for nesting. Population augmented in fall and winter by migrants from northern parts of range. A dense population is found in winter between Tampa Bay and Cape Sable (Root 1988). Present throughout the Keys to the Marquesas; recorded at the Dry Tortugas. CBCs, from three points within the study area, 1977 to 1987: average yearly total 46; maximum yearly total 170; minimum, 8. While the average of total counts at Coot Bay-Everglades National Park was 13, at the Lower Keys it was 9, and at Key Largo-Plantation Key was 5.

Seasonality. Nests March to July. Migrants begin arriving October.

Habitat/Natural History. In the study area, a bird of mangrove shorelines and mud flats. Roosts in mangroves by day. Nests in mangroves and other trees; nests singly and in colonies, often of mixed species. Nest of twigs. Eggs, 2 to 3; incubation, 21+ d; 3.5 wk to fledging.

Foraging. Principally in areas exposed by receding tides and where crustaceans can be found. Forages along mangrove shorelines and on exposed tidal flats distant from shorelines. Forages solitarily. Principal foraging methods: "standing while looking for prey" and "walking slowly." Forages at night; also in daylight, with receding tides.

Prey/Food. "The Yellow-crowned is a dietary specialist on crustaceans" (Hancock and Kushlan 1984). Fish and a variety of invertebrates including mussels also taken.

Comments. Difficult birds to census; the size of the study area's population is not known. Oil washing into mangroves and over tidal flats would destroy the fiddler crabs (*Uca* sp.) and other crustaceans upon which the heron feeds.

2. Ibises and Spoonbills [Family Threskiornithidae]

a. Ibises

Glossy Ibis - *Plegadis falcinellus*

Occurrence in Study Area. PR, but sporadic in the study area. A colonist from the Old World, this ibis nested in Florida originally at Lake Okeechobee. By the 1970s, nesting in Conservation Area Three, and, more recently, attempting to nest in Taylor's Slough, Everglades National Park (Dunstan 1978b). Migrations probably overfly Florida Bay and the general area, the species generally shunning marine conditions (J. Ogden, pers. comm. 1989, biologist, U.S. National Park Service). Can be seen at times foraging at Cape Sable and nearby tidal flats. CBCs, 1977 to 1987, from two points in the study area (Coot Bay-Everglades National Park and Key Largo-Plantation Key: average yearly total 77; maximum yearly total 473; minimum, zero (two times).

Seasonality. As in other ibises, nesting characterized by "opportunism" and not always predictable. Ibises disperse widely after breeding and exhibit pronounced nomadism.

Habitat/Natural History. Fresh water and, to much lesser extent, marine wetlands. Nests in variety of trees: mangroves, buttonwood, Brazilian pepper, etc. Nests and roosts communally and with other wading birds.

Foraging. Much as in White Ibis.

Prey/Food. Much as in White Ibis.

Comments. Abundance within the study area not great; occurrence sporadic.

White Ibis - *Eudocimus albus*

Occurrence in Study Area. PR. Range in process of change. Substantial proportion of nesting was concentrated in the coastal Florida colonies of Everglades National Park mangroves and Florida Bay mangrove islets (Frank Key, Cowpens, etc.). In 1986 and 1987, Frederick and Collopy (1988) found that <2% of former numbers nested there. As with the Wood Stork, the White Ibis is apparently responding to changing habitats (human modification of the freshwater hydroperiod and inadequate prey) and shifting breeding northward in Florida and beyond. Reduced numbers continue to breed irregularly and with considerable nesting failures in mangroves fringing the northern rim of Florida Bay. Numbers can still be seen foraging among the mangrove roots at low tide and on exposed tidal flats. CBCs, from three points within the study area, 1977 to 1987: average yearly total 2,835; maximum yearly total 8,353; minimum 1,309.

Seasonality. An "opportunistic" species in nesting which can begin as early as March or be delayed to as late as September (Kushlan 1974). Numbers foraging around the Bay are unpredictable.

Habitat/Natural History. The species is adapted for wide habitat shifts. In South Florida, it exhibits intra-regional population movements between wetland ecosystems in response to changes in prey availability.

Marine and freshwater wetlands, lawns, pastures, dry fields, etc. From mangrove nesting colonies, birds have historically flown inland to forage in drying areas of Shark Valley sloughs and other freshwater tributaries of Florida Bay. Nest, twigs in forks of mangroves or bushes, sometimes of fibers in sawgrass; also on the ground. Eggs, 2 to 4; incubation, 22 d; fledges 5 to 6 wk. Colonial in nesting and usually with other species of waterbirds.

Foraging. Versatile. Usually in shallow water (10 cm) but also on beaches, lawns, etc. Visual or tactile. Sighted prey "plucked" from substrate. Variations of probing are: "groping" or moving agape bill along bottom of water; "plunging" agape bill into substrate; "spoonbilling-swinging" submerged agape bill from side to side through water column; "stationary-probing," "step-probing," and "multi-probing." Frequently forage in small groups or in large flocks (Kushlan 1974).

Prey/Food. Wide prey acceptability (Kushlan 1974). Diet emphasizes slow-moving or sedentary animals of the bottom and within aquatic growth; crustaceans, worms, insects, and, when abundant, small fish.

Comments. Points of concern are: (1) the presently dwindling numbers in the southern part of Florida (Florida Bay and other places in the study area); (2) probers and pickers from mud and marine flats vulnerable to oil washes over these areas; and (3) social feeding increases vulnerability of the species to pollution.

b. Spoonbills

Roseate Spoonbill - *Ajaia ajaja*
Florida Species of Special Concern (FGFWFC 1989)

Occurrence in Study Area. PR, WR, SR. According to Allen (1942), Florida Bay breeding population composed of migrants from south of Florida which reach there in fall and return south in the spring, while a spring flight of subadults from south of Florida migrates there in the spring and returns south in fall. The subadults may be the spoonbills seen along coastal areas in summer (Ogden 1978c). Nesting has been almost entirely on mangrove islets of Florida Bay (but see beyond), and these birds forage primarily in adjacent mangrove areas. Spoonbills also forage extensively in tidal ponds and sloughs along the Upper Keys from Key Largo to Lower Matecumbe. Foraging also occurs in mangroves east of U.S. 1 between Turkey Point and Barnes Sound (Owre unpubl. data). CBCs, 1977 to 1987, from two points in the study area (Coot Bay-Everglades National Park and Key Largo-Plantation Key; numbers of birds from Lower Keys' count negligible): average yearly total 335; maximum yearly total 802; minimum, 39. In CBCs from Coot Bay-Everglades National Park, Root (1988) found the second highest numbers along the Gulf coast.

Powell et al. (1989) summarized the known historical and current information about the population of this bird. At the lowest point in spoonbill numbers, only 15 pairs remained in Florida Bay. Subsequent to establishment of adequate legal protection for the birds, 100 breeding pairs were surveyed in 1948 to 1949. This population then doubled every ten years reaching 1,254 pairs in 1978 to 1979. In addition to its traditional nesting sites on Florida Bay islets, the birds were now nesting in the Bay's mangrove fringe. At the 1984 population survey, the population had declined 64% from its peak of 1978 to 1979. Low reproductive success and therefore a low rate of recruitment continues. This is apparently correlated with the reduced freshwater input from the Everglades and lack of adequate food resources.

Seasonality. September to October flocks arrive in east Florida Bay. Nesting November and December, young fledge February (Ogden 1978c).

Habitat/Natural History. Largely coastal in Florida, frequenting mangroves, marshes, sloughs, etc. wherever pools in which small fish collect. Also feed in interior wetlands. Nests of twigs, in forks of mangroves. Eggs, 2 to 3; incubation, 24 d; fledge 35 to 42 d. Young not mature adults before 3 yr. Young and adults disperse March to April from Cape Sable area to Tampa Bay (Ogden 1978c).

Foraging. Tactile. Walks through shallow water swinging head and neck from side to side, the spatulate-shaped mandibles slightly agape. Bill snaps shut reflexively when prey touched. This is a "medium" foraging depth species, with maximum foraging depth about 20 cm (Powell 1987). When water levels in Florida Bay are highest and too deep for foraging, spoonbills migrate from the Bay (Powell 1987). Much foraging at night (Powell 1987).

Prey/Food. In Florida Bay, largely fish: *Fundulus*, *Gambusia*, *Cyprinodon*, and *Mollienisia* (Allen 1942). Crustaceans (*Uca* sp.) and insects also taken.

Comments. The spoonbill population has recovered from its low point early in the Century. Growth of the population has now ceased and once again begun to decline, this time as a result, apparently, of inadequate food supplies resulting from inadequate flow of fresh water from the Everglades. The spoonbill population is now stressed. Oil washing into feeding areas of nesting adults and/or of newly fledged young could provide a disaster to the population. What a dreadful tragedy in conservation annals it

would be were any considerable additional mortality to impact upon these birds -- mortality resulting from pollution of the Florida Bay environment! Moreover, Florida Bay's spoonbills constitute a subpopulation of this species and it has "traditions" (where, when to migrate, and nest, etc.) which could easily be broken. Finally, there is not a more delightful sight to residents and tourists alike than spoonbills flying across the landscape.

Allen (1942) commented on dangers of oil drilling to this species and also noted that, under some circumstances, oil drilling and spoonbills need not be incompatible.

3. Storks [Family Ciconiidae]

Wood Stork - *Mycteria americana*
Florida Endangered, USFWS Endangered (FGFWFC 1989)

Occurrence in Study Area. PR. From 1967 to 1982, South Florida's Wood Stork population decreased about 75% (Kushlan and Frohring 1986). The population has apparently shifted nesting northward into Florida, Georgia, South Carolina, etc. (Frederick and Collopy 1988). Altered hydrography has so changed seasonal water levels that there is inadequate available food at nesting time (Ogden 1985). Reduced numbers continue to nest at some traditional sites in mangrove swamps between Cape Sable and Maderia Bay (e.g., Lane River, Old Lane River, East River, Cuthbert Lake, and Alligator Lake). The storks did not nest historically on mangrove islets in Florida Bay and have been uncommon on the Keys. Mangrove-nesting birds forage extensively in freshwater drainage systems that terminate at Florida Bay; here, as water levels dropped in winter and spring, prey became trapped in isolated ponds in depressions of the substrate and were available to foragers. Both in and out of nesting season, storks also forage in the mangroves and the peninsula's southern rim. CBCs, from three points within the study area, 1977 to 1987: average yearly total 221; maximum yearly total 693; minimum, 28. All but 3 of these birds were recorded from Coot Bay-Everglades National Park.

Seasonality. Nesting onset variable, being dependent upon falling-water levels in the Everglades drainage system. Nesting assemblages may form from November to January, and as late as mid-April (Frederick and Collopy 1988). Juveniles disperse widely. Some birds are usually present in the general area outside of the nesting season.

Habitat/Natural History. Freshwater, brackish, and marine wetlands of many sorts. Wades. Colonial, nesting in large rookeries. Nests of sticks, in high cypress trees or mangroves. Eggs, 2 to 4; incubation, to 32 d; young fledge 8 to 9 wk.

Foraging. "Walks slowly," bill in water and slightly agape; when bill touched, snaps shut on prey. Often in groups, sometimes to belly in depth (50 cm). If vegetation present, "foot stirs" above plant growth. Regularly uses thermals to ascend to altitude, then glides effortlessly, this repeated up to as far as 130 km (Ogden 1978a).

Prey/Food. Chiefly small fish, 2- to 12-cm long; spectrum of aquatic animal life as well.

Comments. Nesting rookeries usually sufficiently inland that oil penetration to them unlikely. Foraging birds along the mangrove fringe certainly vulnerable in event of spill. An endangered species, *any* unnatural mortality to the population is of concern. Mortality particularly serious in view of this being a K species, with deferred maturity, long nest life of young, and extended parental care.

E. Waterfowl [Order Anseriformes, Family Anatidae]

American Wigeon (=Baldpate) - *Anas americana*

Occurrence in Study Area. WR, MV. Many birds pass through South Florida via migration corridors into the Caribbean (Bellrose 1980). CBCs, from three points within the study area, 1977 to 1987: average yearly total 691; maximum yearly total 1,730; minimum, 5. Of those recorded within the study area, none were found outside of Coot Bay-Everglades National Park.

Seasonality. Begin arriving in October, arrivals peak in November, numbers decline rapidly in February and early March, most individuals gone by May (Bellrose 1980).

Habitat. Winters in both freshwater and brackish areas. Coastal estuaries, mangrove lakes, mangrove fringes, southwest coastal areas, etc. Associates with other species.

Foraging. A dabbling duck, often "tipping"; also feeds from surface, thrusting head and neck into water. Robs Coots (*Fulica americana*), Canvasbacks (*Aythya valisineria*), and other diving ducks of food they bring to the surface. Jumps into flight.

Prey/Food. Predominantly plant material, stems and leafy parts of aquatic plants (not seeds); animal food (only about 6% in data presented in Howell 1932) includes insects and small molluscs.

Comments. Potential vulnerability to oil as with other surface-feeding ducks.

Blue-winged Teal - *Anas discors*

Occurrence in Study Area. MV, WR. Most of the population winters south of the U.S. Important migration corridors pass through Florida (Bellrose 1980), and part of the fall, winter, and spring birds in the study area are migrants pausing en route. Some individuals winter. CBCs, from three points within the study area, 1977 to 1987: average yearly total 2,064; maximum yearly total 5,610; minimum, 130.

Seasonality. One of the earliest fall migrants, a few reaching Florida in late August (Howell 1932); numbers peak in November and most have departed northward by April, a few remaining into May (Bellrose 1980).

Habitat. Primarily shallow waters fringing freshwater (to which partial), brackish, and coastal areas. Variable numbers forage along coastal mangroves, in mangrove lakes (Cuthbert, Coot Bay, etc.), and in bays, estuaries, and lagoons. Recorded at the Dry Tortugas. When not breeding, gregarious. Large flocks often gather to forage. Sometimes seen on the open ocean. Jumps into flight.

Foraging. A dabbling duck but it does not "tip" as frequently as most dabblers, most often merely extending the neck and head into the water or feeding from the surface.

Prey/Food. Largely plant material, seeds, stems and leaves; animal food: crustaceans, insects, and molluscs (Howell 1932).

Comments. During the long period while migrants pass through the study area, extensive oil pollution could affect large numbers of these, thus reducing both wintering and breeding populations from large areas. During any winter month, this is the most abundant surface-feeding duck in the Everglades estuaries (Kushlan et al. 1982). Interestingly, of more than 200 banded Blue-winged Teal recovered in South Florida, 85% had been banded in the Midwest.

Lesser Scaup - *Aythya affinis*

Occurrence in Study Area. WR, MV. Found throughout the peninsula's freshwater areas and inhabits mangrove forests and lakes of the peninsula's southern rim. Found over much of Florida Bay, Whitewater Bay, and Coot Bay; coastal marshes, inshore waters of the Southwest coast, and Upper Keys. Occasionally in Lower Keys (Greene 1946). Bellrose (1980) speaks of Lesser Scaups "five to ten miles offshore" in the Gulf of Mexico. This is the most abundant wintering diving duck in South Florida (Kushlan et al. 1982). CBCs, from three points within the study area, 1977 to 1987: average yearly total 1,389; maximum yearly total 10,396; minimum, zero (one time).

Seasonality. First migrants appear in October; numbers increase rapidly in November, peak in February, then diminish, declining rapidly in March; some linger into May (Bellrose 1980). Migration corridors lead to Florida from central Canada, Ohio-Michigan area, and the Atlantic coast. These continue into Cuba and points southward.

Habitat. Estuaries, protected bays, mangrove lakes, and inshore waters to several kilometers offshore; and depths of 5 to 14 m (Bellrose 1980). May form large rafts of thousands (Palmer 1976a).

Foraging. Dives; forages on the bottom and through the water column, most commonly at 5- to 8-m depths (Palmer 1976a).

Prey/Food. In marine areas, majority of diet is animal material: gastropods, fish, shrimp, etc.; plant food largely seeds and pods of aquatic plants, varying with locality.

Comments. The species' abundance, its foraging underwater, rafting in flocks, etc. make this duck significantly vulnerable to oiled waters.

Mottled Duck - *Anas fulvigula*

Two subspecies of this duck occur in the southern U.S.: *A. f. fulvigula.*, restricted to the lower two-thirds of the Florida peninsula and called by some, the Florida Duck; and *A. f. maculosa* found along Gulf of Mexico coastal areas from Louisiana into Mexico.

Occurrence in Study Area. PR. Interior and coastal wetlands. After breeding, there is some shifting about of the population by short localized movements (Stieglitz and Wilson 1968). Breeds sparingly in the coastal salt flats, meadows, marshes, sounds, and bays. The bulk of the State's population is centered well north of the southern rim of the peninsula. CBCs, from three points within the study area, 1977 to 1987: average yearly total 94; maximum yearly total 538; minimum, 2. None of these ducks were recorded outside the Coot Bay-Everglades National Park area.

Seasonality. Breeds February to July, but peak is March to April (Stieglitz and Wilson 1968).

Habitat. Coastal and interior wetlands. In the study area, it breeds and is found year-round within coastal salt meadows, marshes, mangrove lakes, bays, etc. (see Gusey 1981 figs.: 5.5, 5.6, 5.7, 5.9). Bent (1923): parties of the birds are said to leave freshwater ponds and fly to sand bars on the inner sides of Keys where they spend the night in pools or coves near the mangroves, returning at day. Nest, on ground, well hidden by vegetation; also built on levees and spoil islands. Stieglitz and Wilson (1968) found nests under mangroves. Jumps into flight. At hatching, young follow the mother. Adults go through a molting period and are then flightless for at least three weeks.

Foraging. A dabbling duck.

Prey/Food. Stieglitz (1972) found freshwater and marine-foraging birds took quite different food in these situations, this varied seasonally in both areas. Plant food predominated. Animal food of coastal birds included gastropods, pelecypods, crabs, and insects. In brackish water, widgeongrass *Ruppia maritima* and spring naiad *Naias marina* are important.

Comments. Oil drifting or washing into mangroves and coastal marshes could affect birds of these areas, particularly during nesting and immediately after when the adults are flightless during molt and young are not yet flying.

Northern Pintail - *Anas acuta*

Occurrence in Study Area. WR, MV. Many continue into the West Indies (Bellrose 1980). Seasonally there are numbers at Whitewater Bay, Coot Bay, and other mangrove lakes, and in Florida Bay. CBCs, from three points within the study area, 1977 to 1987: average yearly total 2,716; maximum yearly total 13,189; minimum, 3. Of those pintails recorded, all were from Coot Bay-Everglades National Park area.

Seasonality. Small numbers arrive in early October, bulk in late October and early November (Bellrose 1980). Largely gone from the State by end of March.

Habitat. Brackish and marine situations of coastal areas. Florida Bay and the Southwest Coast. According to Bent (1923), seacoast-wintering birds "often spend day well out on ocean, flying in at night to feed in shallow tidal estuaries, on beds of *Zostera* or on mud and sand flats where the birds find plenty of small molluscs."

Foraging. Dabbles, "picks" from surface, and forages on land.

Food. A preponderance of plant material, seeds often emphasized; animal food: molluscs, worms, insects, etc. (Bellrose 1980).

Comments. Vulnerable to oil as most ducks.

Red-breasted Merganser - *Mergus serrator*

Occurrence in Study Area. WR. Distributed largely along the length of Florida's coastline. Numerous within Florida Bay, inshore waters along the Keys, and Southwest coast; present at the Dry Tortugas. CBCs at Key Largo-Plantation Key area totaled 1,000 birds in 1980 CBC. CBCs, from three points within the study area, 1977 to 1987: average yearly total 1,259; maximum yearly total 2,214; minimum, 622.

Seasonality. October to May; arrivals peak in December. Northward movements begin in March (Palmer 1976b).

Habitat. Common along mangroves of the mainland, particularly in fairly calm waters of protected areas; but ranges into the inshore ocean off the Keys and Southwest coast. Usually runs into flight. Bathes much while swimming. Often rests ashore.

Foraging. A diving duck, pursuing fish underwater. Small prey are swallowed underwater; larger prey are swallowed at the surface or above it (Palmer 1976b). Frequently in small groups and these may forage "cooperatively."

Prey/Food. Mostly fish; some crustaceans.

Comments. Vulnerability to oil is great for a swimming-diving species. W. Robertson (pers. comm. 1989) observed that after oil entered the Tortugas lagoon (1964), the wintering population of this bird there "disappeared." Although this bird is only a WR, it must be kept in mind that any significant mortality in South Florida will be reflected elsewhere on local breeding grounds. Clapp et al. (1982b), noting that a substantial proportion of this bird's population winters in coastal marine habitats of the southeastern U.S., stated that development of petroleum resources in the Southeast presents "some hazard" to the stability of its populations in North America.

Ring-necked Duck - *Aythya collaris*

Occurrence in Study Area. WR, MV. Within the study area, much as the Lesser Scaup; probably in somewhat smaller numbers since the Ring-necked frequents marine situations to a lesser extent than fresh water (Howell 1932). Important migration flyways lead into Florida and continue southward. CBCs, from three points within the study area, 1977 to 1987: average yearly total 739; maximum yearly total 5,626; minimum, zero (one time). Of those ducks recorded from the eleven-year period under consideration, all were seen from the Coot Bay-Everglades National Park area.

Seasonality. Migrants begin arriving in October. Numbers peak in late November, decrease rapidly in February, and are largely gone by mid-April (Bellrose 1980).

Habitat. Much the same as for the Lesser Scaup. Brackish mangrove lakes are frequented as are brackish-water lagoons. Bent (1923) wrote that individuals may spend the night on the ocean and come to fresh water by day.

Foraging. A diving duck, usually more active in shallower water (often <2 m deep) than other diving ducks (Bellrose 1980). Runs into takeoff.

Prey/Food. Primarily plant material, seeds, stems, leaves, tubers, etc.; animal material: snails, to a large extent (Bellrose 1980).

Comments. Migrants passing into and out from the study area create the potential for large numbers to encounter oil pollution.

F. Vultures, Hawks, and Falcons [Order Falconiformes]

1. Vultures [Family Cathartidae]

Black Vulture - *Coragyps atratus*

Occurrence in Study Area. PR. Chiefly the mainland areas, being "rare in the Keys" (Sprunt 1963). CBCs, from three points within the study area, 1977 to 1987: average yearly total 105; maximum yearly total 213; and minimum, 35 birds from the Coot Bay-Everglades National Park area. From the two other points (Upper and Lower Keys), a total of 2 birds was recorded during these 11 years! Clearly, this is a bird of the mainland margin of the study area and not of the Keys.

Seasonality. Nests January to July.

Habitat/Natural History. Nests on the ground, under palmetto clumps, a stump, or a log. Eggs, 2 to 3; incubation, 30 d; age at fledging not known. When not breeding, birds congregate at sunset at roosts usually in trees.

Foraging. Entirely visual. Sights prey from altitude. Foraging birds also "clue" to prey locations from watching the behavior of Turkey Vultures (which in addition to visual clues, have olfactory abilities). Black Vultures are said to attack dying and small animals which Turkey Vultures apparently seldom do.

Prey/Food. Carcasses, wounded animals, eggs and young of colonial waterbirds and others, as well as small animals.

Comments. Mortality of birds and other animals along mainland shorelines would undoubtedly attract feeding concentrations of these and Turkey Vultures.

Turkey Vulture - *Cathartes aura*

Occurrence in Study Area. PR, WR, MV. Three populations present: (1) A small breeding one, assumedly relatively sedentary, is found around the southern tip of the Florida peninsula; there are concentrations of these birds at Big Pine Key, Cape Sable, etc. This population is subspecifically the same (*C. a. aura*) as that in Cuba, the Bahamas, Western North America, and Central America (Brown and Amadon 1968); (2) A large wintering population, *C. a. septentrionalis*, derived from much of eastern North America (Gaby 1982); and (3) MVs derived from the preceding area, but departing Florida. See Darrow (1982) who reported 1,000+ kettling over Key West on 12 December; other such flights have been recorded. CBCs, from three points within the study area, 1977 to 1987: average yearly total 626; maximum yearly total 878; minimum, 450.

Seasonality. Nests early March into May. Influx of fall birds begins in October. Non-resident population has departed by May (Gaby 1982).

Habitat/Natural History. Virtually ubiquitous throughout the study area's land and littoral landscapes. Roosts in trees, sometimes on ground, communal after breeding. Nests on ground, under palmettos, under tree-falls, in caves, etc. Bathes at shorelines; much time in trees sunning.

Foraging. By olfaction and vision. The former at low altitude, not far above forest canopy or open ground. When soaring at altitudes, locates feeding assemblages and sees other vultures descending to feed. Frequents shorelines and urban garbage dumps.

Prey/Food. Dead animals of all sorts, from fresh to putrid. Frequents nesting rookeries of wading birds where searches the ground for dead and also takes eggs and probably small young from nests.

Comments. The large concentrations of wintering birds in South Florida (as many as 4,000 in Dade County alone-[Gaby 1982]) and their extreme mobility (patagial-tagged birds from Dade County seen in roosts near Lake Okeechobee and at other localities distant from tagging [Gaby 1982]) suggest that large kills of fish or aquatic birds might attract more than strictly local vultures in great numbers. Ingestion of carcasses of oil-killed animals could cause mortality and sub-lethal effects. The wintering population is drawn from a large part of eastern U.S. and Canada (Gaby 1982) and mortality of numbers of it could be felt over a large nesting range. The South Florida breeding population is small and any mortality of these birds would be a matter for concern.

New World Vultures have been reduced in numbers. Unusual mortality to such a population is to be avoided.

2. Kites, Eagles, Hawks, and Allies [Family Accipitridae]

a. Ospreys [Family Accipitridae: Pandioninae]

Osprey - ***Pandion haliaetus***
Florida Species of Special Concern (Monroe County), CITES II (FGFWFC 1989)

Occurrence in Study Area. PR, MV. Birds of the breeding population disperse northward locally (Ogden 1978b). Ospreys of populations in North Florida and points beyond pass through southern Florida in migration to the Caribbean, Central, and South America. These birds probably linger for varying periods. CBCs, from three points within the study area, 1977 to 1987: average yearly total 142; maximum yearly total 204; minimum, 91.

Seasonality. Nests November into April. Migrants present September to November and March to April (Ogden 1978b).

Habitat/Natural History. Trees, utility poles, and channel markers support the large nests of this species and afford the birds important outlooks. Nests along the Florida Keys, particularly the Upper Keys near the mainland, to the Marquesas; on mangrove islets within Florida Bay (along the northern rim of the Bay), and along the Southwest Florida coast. Nests are bulky structures of sticks used for several years; linings of seaweeds and debris taken from shorelines or the water. Young hatch after 30 to 35 d, and fledge after 8 wk; immature until 2 yr.

Foraging. Searches in flight for prey and "dives" from soaring or from hovering--from heights as great as 15 m. The plunge may carry a bird to a depth at which only wing tips are emergent. A fish is carried by both feet.

Prey/Food. Almost exclusively fish, capturing "whichever species is most available" (Westall 1986).

Comments. Osprey populations of the continent were much affected in the 1950s and 1960s by pesticides, but have begun to stabilize and increase (Westall 1986). Declines in the Florida Bay populations are ongoing, however. Kushlan and Bass (1983a) postulated a 58% decrease between 1973 to 1980 and they attributed this to reduced productivity because of lower food supplies. Fleming and Kline (1987) found the number of nesting birds low and productivity variable, but believed the population stabilized. Bowman et al. (1987), however, found that birds fishing exclusively in Florida Bay produced fewer offspring than those nesting along the Keys which fished in inshore coastal waters, suggesting that birds feeding in the Bay are indeed experiencing difficulty "due to an inadequate food supply."

Oil pollution in the Bay or in inshore waters along the Florida Keys to the Marquesas and beyond could seriously impact this breeding population from: (1) reduction of food supply; (2) oiling of adults when diving for prey; and (3) oil on seaweeds and other shorewise-gathered nesting materials, with resultant oiling of eggs, young, and adults. Migrating populations could be affected by one and two above.

b. Kites, Eagles, and Hawks [Family Accipitridae: Accipitrinae]

American Swallow-tailed Kite - *Elanoides forficatus*
USFWS Under Review 5 (FGFWFC 1989)

Occurrence in Study Area. SR, rarely WR. Mangroves of Key Largo and southern rim of the peninsula. Nests in black mangroves. Migrants from southeastern U.S. traverse the study area in migration; recorded Dry Tortugas in migration. Eleven years of CBC counts from three points within the study area between 1977 and 1987 showed no birds present.

Seasonality. February to October. Nests February to April.

Habitat/Natural History. Mixed countryside including cypress and pine forests, mangroves, grasslands, along rivers, estuaries, etc. Nests in tall trees including cypress, pines, mangroves, and casuarinas. Incubation, 28 d; fledges, 36 to 42 d. Bathes and drinks while in flight.

Foraging. Entirely while in flight; frequently eats while flying.

Prey/Food. Particularly large flying insects, also lizards plucked from trees, birds and their eggs and nestlings, arboreal snakes, etc. (see Bent 1937).

Comments. Foraging method and diet remove this species from vulnerability to oil pollution.

Bald Eagle - *Haliaeetus leucocephalus*
Florida Threatened, USFWS Endangered, CITES I (FGFWFC 1989)

Occurrence in Study Area. PR, WR. South Florida breeding population is the largest in the State. Estimate of pairs within the study area: 51 to 59 (Robertson 1978c), now somewhat smaller. Juveniles may migrate north to eastern Canada; older birds disperse locally after breeding. Presumably some northern birds enter the areas in winter. CBCs, from three points within the study area, 1977 to 1987: average yearly total 29; maximum yearly total 39; minimum, 21.

Seasonality. Nests repaired early fall, eggs as early as October. Nests with eggs October to March.

Habitat/Natural History. "Primarily near seacoasts, rivers and large lakes, breeding in tall trees...." (AOU 1983). Nests reused and added to each year. Incubation, 45 d; time to fledging, 10 to 12 wk.

Foraging. Varied: fish by "plunging" or "plucking" from surface; waterfowl seized on water or overtaken in flight; mammals seized from water or land; carcasses fed upon along shorelines.

Prey/Food. Fish, birds (ducks, coots, cormorants, grebes, etc.), mammals, carcasses.

Comments. Although King and Sanger (1979) list the OVI of this eagle as 58, which is their category of "watch to determine mortality and then take remedial measures," calculated in South Florida, this OVI should be much higher. Important considerations are: (1) largest concentration of breeding Bald Eagles in the Southeast (Green 1985); (2) the eagles are concentrated about the coastal areas and islets and forage here; (3) foraging is principally for fish and aquatic birds; (4) eagles may get wet securing live prey; (5) they readily feed on carcasses; (6) eagles wade into the water to bathe; (7)

some require six years to maturity; (8) not all adults breed each year; (9) any unusual mortality of a reduced population is serious; and (10) much public interest is directed towards this bird, the national symbol.

Literature discussing effects of oil ingested by birds of prey in nature is lacking. From the *Exxon Valdez* oil spill, however, some preliminary information is available (Eagan 1989). Exxon has 148 carcasses of Bald Eagles in cold storage. Not only were birds killed outright, but some suffered damage to the extent that they could not fly adequately, and others were said to have suffered blindness and infections.

Broad-winged Hawk - *Buteo platypterus*

Occurrence in Study Area. WR, MV. In the U.S., the largest wintering numbers are in South Florida, along the coasts and the Keys (AOU 1983). Root (1988) reported the densest CBCs concentration in the U.S. to be west of Key Colony Beach where a ten-year average of 0.37 was seen per party hour. CBCs, from three points within the study area, 1977 to 1987: average yearly total 17; maximum yearly total 33, minimum, 4. Some of the birds reaching Florida apparently continue in migration. Atherton (1981) reported kettling of the hawks over the Keys, and Howell (1932) reported large flocks over Key West. Primary wintering area of the species is Central America.

Seasonality. Migrants and wintering birds, October to May.

Habitat/Natural History. Fairly dense wooded areas. Mangroves and hammocks of the Keys are frequented. Open woodland infrequently. Soars at times during the day.

Foraging. Usually watches from perches low down in the forest. Launches itself at prey. Changes positions in the woodland by flying amongst the trees.

Prey/Food. Small mammals, snakes, lizards, large insects, and small birds.

Comments. Although the wintering birds remain inconspicuous within dense growths, and oil vulnerability should be minimal, large migrating groups could be attracted to widespread numbers of weakened birds resulting from oil spills.

Northern Harrier (=Marsh Hawk) - *Circus cyaneus*
CITES II (FGFWFC 1989)

Occurrence in Study Area. WR, MV. Common migrant through the Keys (Greene 1946). CBCs, from three points within the study area, 1977 to 1987: average yearly total 24, maximum yearly total 41; minimum, 9.

Seasonality. Pulses of migration, September to October and February to March. Wintering birds and migrants, September to May.

Habitat/Natural History. Marshes, coastal prairies, shorelines. Common at Cape Sable.

Foraging. Entirely while flying; estimated may cover 160 km/d (Root 1988). Territory size in winter, about 1.6 km^2 (Root 1988). Usually 7 to 10 m above ground, sometimes to 15 m.

Prey/Food. Mammals to size of rabbits, birds to size of ducks, amphibians, reptiles, crustaceans, and insects.

Comments. Migration lines tend to follow the coasts; while migrants are in passage, any extensive areas with weakened or dying animals could attract numbers of harriers.

Red-shouldered Hawk - *Buteo lineatus*

Occurrence in Study Area. PR. Throughout land areas including Keys and mangrove forests. Birds from extreme southern part of the peninsula have been considered a subspecies (*B. l. extimus*) which is paler and smaller than peninsular birds (*B. l. alleni*); both are distinct from *B. l. lineatus* of eastern North America (Brown and Amadon 1968). CBCs, from three points within the study area, 1977 to 1987: average yearly total 61; maximum yearly total 101; minimum, 35.

Seasonality. Nests approximately January to March.

Habitat/Natural History. According to Greene (1946), partial to hammocks on keys such as Big Pine and Sugarloaf. Common at Cape Sable, around Flamingo and mangrove forests in general. Nests on some large, non-mainline keys in Florida Bay, e.g., Frank Key (Ogden 1974b).

Foraging. Watches on perches both in the forest and exposed, from which it launches after prey. Nests well up in trees. Territorial.

Prey/Food. In Florida: snakes, lizards, frogs, and insects (Howell 1932).

Comments. Oil spill would have to be widespread to endanger large numbers of this well-distributed population. Note: resident birds represent the "tip" or termination of a peninsular gradient of recognizable morphological characteristics; thus, they are unique.

Sharp-shinned Hawk - *Accipiter striatus*

Occurrence in Study Area. WR, MV. Abundant during migration, dozens or hundreds a day passing along shoreline areas near Card and Barnes Sounds (Owre unpubl. data). Considerable numbers have been reported in fall at the Dry Tortugas. CBCs, from three points within the study area, 1977 to 1987: average yearly total 12; maximum yearly total 40; minimum, 6. Numbers of wintering birds, as indicated by these counts, are in contrast with the numbers present during migration.

Seasonality. Migration pulses, October to November and March to April. Wintering birds and migrants, October to April.

Habitat/Natural History. Virtually the entire landscape, particularly areas of scattered shrubs and trees; in winter, frequently in dense woodland such as hammocks and mangroves.

Foraging. Prey rapidly pursued in maneuvering flight, often through woodland.

Prey/Food. Almost entirely small birds, some mammals, lizards, and insects.

Comments. Vulnerability in event of oil pollution probably slight unless numbers of weakened shorebirds along littoral areas coincide with periods of migrating hawk abundance.

Short-tailed Hawk - *Buteo brachyurus*

Occurrence in Study Area. The entire North American population of this species is found in winter in South Florida; *some* of these birds are permanent residents and breed here, the remainder migrating to breed in Central and North Florida (Ogden 1974a). The species is present, therefore, year-round about the perimeters of Florida Bay including the Upper and Lower Keys, to Key West and beyond. CBCs, from three points within the study area, 1977 to 1987: average yearly total 5; maximum yearly total 10; minimum, zero. It is interesting to note that over the eleven years of the CBCs totaled here, 58 hawks were recorded from the Coot Bay-Everglades National Park area, none from the Upper Keys, and 7 from the Lower Keys.

Seasonality. Non-nesting birds migrate into South Florida in October and return north in February. In South Florida, eggs laid March or April. Young fledged June.

Habitat/Natural History. Nests and roosts in stands of large cypress, hardwoods bordering rivers, mangroves, pines, and other trees bordering sizeable prairies, marshes, etc. Soars at altitude during portions of the day.

Foraging. Slow-soaring at medium to great heights. Prey captured by swift, often vertical dives into tree or bush canopies.

Prey/Food. Predominantly small birds, e.g., Red-winged Blackbirds (*Agelaius phoeniceus*) and Eastern Meadowlarks (*Sturnella magna*) commonly taken (Ogden 1978d).

Comments. The Florida population probably numbers no more than several hundred (Ogden 1978d); although the species occurs in Central and South America, migration between the two populations is not known. Since the birds are present year-round along the Florida Bay perimeter and since it is a bird-catching hawk, the potential for capture of weakened, oil-soaked, small birds exists. Since the Florida population is so small, any unusual mortality could be significant.

Swainson's Hawk - *Buteo swainsoni*
USFWS Under Review 5 (FGFWFC 1989)

Occurrence in Study Area. WR. Open areas of the mainland and along the Keys. More than 40 years ago, Greene (1946) saw this hawk "almost every year in Key West and along some of the other Lower Florida Keys." CBCs, from three points within the study area, 1977 to 1987: average yearly total 3; maximum yearly total 7; minimum, zero (three times).

Seasonality. November to March.

Habitat/Natural History. This large Buteo breeds on the North American prairies. In some years, large numbers of the birds appear in South Florida to winter. The writer recalls the winter of 1952 when hundreds were present in the farmlands around Homestead.

Foraging. Birds perch on posts, hummocks of soil, or on the ground itself and watch for prey.

Prey/Food. Small mammals, reptiles, insects, etc.

Comments. In most years, this hawk is not present in sufficient numbers to raise concern as to its potential to become oiled should it be attracted to an area of pollution-weakened or killed birds.

3. Falcons [Family Falconidae]

American Kestrel - *Falco sparverius*

Southeastern American Kestrel - *F. s. paulus*
Florida Threatened, USFWS Under Review 2, CITES II (FGFWFC 1989)

Eastern American Kestrel - *F. s. sparverius*
CITES II (FGFWFC 1989)

Occurrence in Study Area. WR. Two subspecies come under consideration here. The Southeastern American Kestrel (*F. s. paulus*) is the breeding subspecies of Florida and adjacent states. Its breeding population has largely disappeared from South Florida (Wiley 1978a). The Eastern American Kestrel (*F. s. sparverius*) breeds over much of the rest of North America and winters throughout South Florida, including the study area, in large numbers. *F. s. paulus* from north of South Florida may winter here but it cannot be reliably distinguished in the field. Kestrels are common throughout the Keys and west to the Tortugas; in fall migration, sometimes abundant on the Keys. All of South Florida has a high concentration of wintering birds, especially the Gulf coast from Naples to peninsula tip (Root 1988). CBCs, from three points within the study area, 1977 to 1987: average yearly total 148; maximum yearly total 196; minimum, 95.

Seasonality. October to April.

Habitat/Natural History. Territorial in wintering area. The males select dense habitats or fringes of clearings; females, more open areas (Mills 1976). Often roosts in empty woodpecker cavities.

Foraging. Sights prey from elevated perches, trees, utility poles and wires, and from hovering. Dives on prey.

Prey/Food. Grasshoppers, other insects, small birds, and mammals.

Comments. This small falcon is relatively safe from oil pollution mortality.

Merlin (=Pigeon Hawk) - *Falco columbarius*
CITES II (FGFWFC 1989)

Occurrence in Study Area. WR, MV. CBCs, from three points within the study area, 1977 to 1987: average yearly total 4; maximum yearly total 6; minimum, 1. These counts reflect the small wintering population of this falcon; much larger numbers are evident in migration.

Seasonality. Pulses of migration, September to October and late March to mid-April; wintering birds and migrants, September to April.

Habitat/Natural History. In Florida, frequents seacoast, salt marshes, mangrove swamps, and edges of open woodlands; migrates along the entire chain of Keys including the Dry Tortugas (Sprunt 1962).

Foraging. Frequently perches on dead branches at the periphery of the mangroves from which it launches out directly after flying birds or makes wide sweeps over water or open ground, returning to perch if unsuccessful. Page and Whitacre (1975) described the species as taking prey on or just as they flush from the ground. At a California lagoon, one Merlin took a minimum of 268 shorebirds over a five-month period.

Prey/Food. Small- to medium-sized birds. In the study area, songbirds, small shorebirds, and large flying insects.

Comments. The general population of this species is declining (Wiley 1978b); this is attributed to habitat modifications, pesticides, eggshell thinning from DDT, etc. (Cade 1982). In the study area, when the falcons become concentrated, sandpipers and plovers rendered clumsy with oiled plumage might be taken.

Peregrine Falcon (=Duck Hawk) - *Falco peregrinus*

Arctic Peregine Falcon - *F. p. tundrius*
Florida Endangered, USFWS Threatened, CITES I (FGFWFC 1989)

Occurrence in Study Area. WR, MV. Of three North American subspecies, two are migratory: the Arctic Peregrine Falcon (*F. p. tundrius*) of Alaska, Canada, and Greenland (Stresemann and Amadon 1979) winters along the Gulf coast and to southern South America; the other, *F. p. anatum*, nested over much of the continent south of the tundra and *was* somewhat migratory, but was extirpated east of the Mississippi during the 1950s and 1960s (Craig 1986). Peregrines migrating through Florida and the study area are *F. p. tundrius* (T. Shirley, pers. comm. 1989, USFWS, Alburquerque, NM), the highly migratory subspecies. While the majority of these birds apparently migrate to the south or westward along the Gulf, it is possible that some remain as winter visitors. CBCs, from three points within the study area, 1977 to 1987: average yearly total 6; maximum yearly total 12; minimum, 3.

Seasonality. September to May.

Habitat/Natural History. Seacoasts, estuaries, bays, lakes, tree-rimmed marshes and prairies, and occasionally urban areas. Dead branches or other suitable lookout perches are requisite. Wintering birds are relatively sedentary and may be localized to a few square kilometers (Snyder 1978).

Foraging. "Still-hunting" most frequent method of search: awaiting potential prey to fly into range for attack. Pursuing falcon dives or stoops at prey from above, striking it with closed feet. The disabled prey is now picked up from the land or from the water (Cade 1982). Effective foraging sites are at concentrations of prey-species.

Prey/Food. Almost entirely birds; waterfowl, shorebirds, and gulls abundantly taken.

Comments. See the discussion of this Endangered-Threatened species in the Dry Tortugas section.

G. Cranes and Allies [Order Gruiformes]

1. Coots and Rails [Family Rallidae]

American Coot - *Fulica americana*

Occurrence in Study Area. WR. Abundant. CBCs, from three points within the study area, 1977 to 1987: average yearly total 2,513; maximum yearly total 14,379; minimum, 78.

Seasonality. October to April; peak numbers December to February In January and February, numbers have reached 35,000 and 36,000 in the area from Barnes Sound, along the coast and inland lakes north of Florida Bay, Cape Sable, Whitewater Bay, and bays of the Southwest Florida coast to Everglades City (Kushlan et al. 1982).

Habitat/Natural History. Brackish bays and estuaries, mangrove lakes (see above). Congregates in flocks; runs into takeoff, its wings and feet splashing the surface. Noisy. Associates with ducks.

Foraging. (1) Dabbles, neck immersed while "tipping" as ducks; (2) dives from swimming position; and (3) stands on muck or other substrate and "plucks from surface." Often rafts into large flocks (1,000+) while foraging.

Prey/Food. Largely plant material: *Chara* (musk grass), other algae, underwater plants, grass and grains, and aquatic insects.

Comments. Oil washing into the northern reaches of Florida Bay and among the Southwest Florida coast could cause heavy mortality in this population as well as compromise wintering grounds for it and several species of ducks.

Clapper Rail - *Rallus longirostris*

Florida Clapper Rail - *R. l. scottii*

Mangrove Clapper Rail - *R. l. insularum*
USFWS Under Review 2 (FGFWFC 1989)

Occurrence in Study Area. PR. Ripley (1977) considers the Clapper Rail conspecific with the **King Rail** (*Rallus elegans*); the AOU (1983) regards the two distinct. The King Rail is found in freshwater marshes inland of the Clapper Rail's brackish/saline habitats. The King Rail is not considered in this report.

Two described subspecies of the Clapper Rail occur in the study area: the Florida Clapper Rail (*R. l. scottii*) breeds along southwest and southeast Florida coasts (Kale 1978), while the Mangrove Clapper Rail (*R. l. insularum*) breeds along the Florida Keys and is probably present at some point along the southern rim of the peninsula (Owre 1978d).

Seasonality. Breeding March to June, possibly longer.

Habitat/Natural History. Coastal, estuarine, and mangrove swamps. According to Ripley (1977), Clapper Rails in Delaware occur where salinities are 7.8 to 5.7 ppt; both Clapper and King Rails are found between 5.7 and 3.7 ppt; and King Rails occur where salinities are less than 3.7 ppt.

Foraging. Walk and run through mangroves, marshes, across exposed tidal flats, etc. Pick and probe for food. Diurnal, crepuscular, nocturnal.

Prey/Food. Largely invertebrates: arthropods (fiddler crabs and other crabs of the mangrove forest floor), molluscs, insects, and small fish.

Comments. No avian species is more characteristic of the mangrove habitat than this rail. Two distinct populations of the species are present in the study area, one of them restricted there. King/Clapper habitats throughout the country have been much reduced, and hunting and pesticides have taken their toll (Root 1988). An extensive oil spill easing into the mangrove shorelines of Florida Bay, the Keys, and the Southwest Florida coast would be tragic insofar as the population of this inhabitant of the mangrove forest floor is concerned.

Sora - *Porzana carolina*

Occurrence in Study Area. WR, MV. CBCs, 1977 to 1987: a total of one bird was recorded from the Lower Keys; no birds were recorded from the Upper Keys; a total of 36 individuals were recorded from the Coot Bay-Everglades National Park area, or an average of 3 birds/yr.

Seasonality. August to April.

Habitat/Natural History. A wide range of marsh habitats. Primarily a freshwater marsh bird, the Sora will enter estuarine and other tidal marshes as well as mangrove swamps (Cramp et al. 1980).

Foraging. Walks on damp ground or wades in shallow water in muddy areas.

Prey/Food. Seeds, other plant materials, snails, insects, and a wide variety of invertebrates.

Comments. Wintering population in brackish areas probably small.

2. Cranes [Family Gruidae]

Florida Sandhill Crane - *Grus canadensis pratensis*
Florida Threatened, CITES II (FGFWFC 1989)

Occurrence in Study Area. PR. "...rare resident of extreme southern Florida...a minimum of about two dozen occur in Everglades National Park and the Big Cypress National Preserve" (Kushlan 1982). Florida subspecies sedentary. CBCs, 1977 to 1987, recorded these birds but once, a total of 14 from the Lower Keys!

Seasonality. Breeding dependent on water levels, therefore variable; usually February to April, as early as December (Walkinshaw 1949).

Habitat/Natural History. Freshwater marshes near interface with coastal mangrove swamp (Kushlan 1982). Birds move about with seasonally-changing habitat conditions. Nesting sites traditional. Nest, a mound of aquatic vegetation usually grounded in shallow water. Adults build "accessory nests" of dry grass for young to rest on by day and for brooding at night (Layne 1981). Eggs, 2; incubation, about 30 d; young walk at hatching and follow parents; fledge about 90 d (Walkinshaw 1949); remain with parents until next breeding season. Gather together at "roosting lakes" from which they fly to feeding grounds in morning. Swim.

Foraging. While walking. In marshes, meadows, pasture, pinelands, etc. "Pick and probe." Larger objects are "threshed" with bill and feet.

Prey/Food. Aquatic plants, rootlets, berries, seeds, grain, worms, grasshoppers, and small vertebrates.

Comments.- Although the cranes are essentially freshwater in habitat, nesting areas in South Florida are close to the mangroves along both the southwest and southeast coasts. There is room for a degree of concern about this population.

H. Shorebirds [Order Charadriiformes]

1. Plovers [Family Charadriidae]

Black-bellied Plover - *Pluvialis squatarola*

Occurrence in Study Area. MV, WR. Common. Keys' shorelines to Marquesas and Dry Tortugas. Root (1988) noted a peak of abundance from CBCs around Naples. CBCs, from three points within the study area, 1977 to 1987: average yearly total 1,552; maximum yearly total 4,767; minimum, 642.

Seasonality. Fall migration peaks, September to October; spring, mid-April to mid-May; many in intervening months. A few remain all summer, but do not nest.

Habitat/Natural History. Nests on the Arctic tundra. In winter, intertidal zone to great extent, but upper beach and even grassy places. Gregarious with other shorebirds. Flocks of own species never large.

Foraging. Frequently near the tide line, frequents mudflats, mangrove shorelines, channels in mangroves, etc. Foraging emphasizes "runs," "pauses," and "pecks." Also feeds at night (Burger 1984).

Prey/Food. Crustaceans, molluscs, insects, and other invertebrates.

Comments. Vulnerability to oiled beaches considerable. Critical periods regarding oil danger probably during migration peaks.

Killdeer - *Charadrius vociferus*

Occurrence in Study Area. PR, WR, MV. In winter: open spaces of the peninsula and Keys. Beaches of the Keys to the Tortugas. Numerous. Far fewer in summer. Expansion of summer range into southern Florida recent (Kushlan and Fisk 1972); in summer, birds appear more numerous around freshwater areas. CBCs, from three points within the study area, 1977 to 1987: average yearly total 176; maximum yearly total 805; minimum, 39.

Seasonality. Wintering birds, October to March.

Habitat/Natural History. Shores of lakes and ponds, coastal prairie, coastal areas such as Cape Sable, levees, improved and filled land in urban-suburban areas, etc. Nest, a depression in ground lined with dried grasses and bits of shells and other oddments, usually near water. Young precocial, leaving nest at hatching. Incubation, 28 d; age at flight, estimated 40 d.

Foraging. Characterized by short "runs" and head bobbing; "picks" prey from surface. In winter, often in small groups.

Prey/Food. Invertebrates, insects (e.g., beetles, grasshoppers, and dragonflies in particular), crustaceans, worms, etc.

Comments. Considering its partiality to inland areas, probably not as vulnerable to oiling as other shorebirds of the areas.

Piping Plover - *Charadrius melodus*
Florida Threatened, USFWS Threatened (FGFWFC 1989)

Occurrence in Study Area. WR, MV. Of the estimated 4,500 remaining in North America (Haig and Oring 1987), the proportion that winters in Florida is not known; Woolfenden (1978b) estimated that not more than several hundred winter in the state at large. Occurs in the study area on Keys' beaches, Cape Sable beaches, and beaches in southern part of Collier County (Woolfenden 1978b). According to A. Sprunt IV (pers. comm. 1989, National Audubon Society, Tavernier), small numbers winter on Keys' beaches. CBCs, from three points in the study area, 1977 to 1987, show a distribution as follows: a total of 12 birds from the Coot Bay-Everglades National Park area; no birds from the Upper Keys; and a total of 51 birds from the Lower Keys, or an average of <5 birds/yr; from the latter area, maximum yearly totals of 14 and 12 were obtained in 1986 and 1987, respectively.

Seasonality. July to May.

Habitat/Natural History. Beaches, tidal sand flats, mud flats, and sand fills.

Foraging. In loose flocks; as typical of plovers: runs, stops, looks around, and then picks up prey from substrate. Also feeds at night (Burger 1984).

Prey/Food. Marine worms, molluscs, crustaceans, beetles, and other insects.

Comments. In consideration of its Threatened status, oil-washed beaches a serious threat to the few individuals of this species.

Semipalmated Plover - *Charadrius semipalmatus*

Occurrence in Study Area. WR, MV. A few non-breeding birds in summer. Sandy beaches, estuaries, and tidal flats along the mainland and the Keys. CBCs, from three points within the study area, 1977 to 1987: average yearly total 316; maximum yearly total 494; minimum, 191.

Seasonality. July to May.

Habitat/Natural History. Breeds on Alaskan and Canadian tundras. In wintering areas, partial to mudflats and intertidal zones. Gregarious with own and other species.

Foraging. Runs, head up, then dabs at substrate; "snatches and probes."

Prey/Food. Invertebrates: molluscs, crustaceans, aquatic insects and their larvae.

Comments. A common wintering and migrating plover of the study area. Considering its habits, oiling is a threat to individuals of the species.

Snowy Plover - *Charadrius alexandrinus*

Southeastern Snowy Plover - *C. a. tenuirostris*
Florida Threatened, USFWS Under Review 2 (FGFWFC 1989)

Occurrence in Study Area. PR. There are two North American subspecies, a western form (*C. a. nivosus*) and the Southeastern Snowy Plover (*C. a. tenuirostris*) (also called the Cuban Snowy Plover) which breeds on the Gulf coast south to Marco Island (just north of the study area) and "probably the Florida Keys" (AOU 1983). Numbers are now very small, Woolfenden (1978a) suggesting <100 pairs. T. Below (pers. comm. 1989, warden, National Audubon Society) found "a very few" nesting on northwest Marco Island in 1989. In winter, found on the Atlantic coast of Florida to Merritt Island (AOU 1983). CBCs, 1977 to 1987, recorded this plover only twice: one bird from the Coot Bay-Everglades National Park area in 1978, and one bird from the Lower Keys in 1987.

Seasonality. Present year-round. Breeds March to July (Howell 1932).

Habitat/Natural History. Dry, sandy upper beaches for breeding. Nest, a scrape in sand, lined with bits of shells; eggs, 3.

Foraging. Forage in typical plover fashion on both upper dry beaches and intertidal beaches where sand being moved about (Woolfenden 1978a). Pats the ground with a foot to disturb prey (Root 1988).

Prey/Food. Crustaceans, molluscs, worms, insects, and other invertebrates.

Comments. Any mortality from oil-washed beaches would be serious in this small population of a Threatened species.

Wilson's Plover - *Charadrius wilsonia*

Occurrence in Study Area. SR, WR, MV. Wintering population apparently small. More northern and local breeding populations move south of Florida in winter. In migration and in summer, along sandy beaches of mainland and Keys; they are a common sight along the Lower Florida Keys during the summer months (Hundley and Hames 1960). From CBCs, Root (1988) found the highest winter concentration in Florida on northern Keys. CBCs, from three points within the study area, 1977 to 1987: average of yearly totals 59; maximum yearly total 133; minimum, 3.

Seasonality. Migration peaks, September to October and February to March. Breeds March to July.

Habitat/Natural History. Sandy areas and tidal flats. Nests well up on beach, sometimes in loose colonies. Nest, a scrape, usually near tuft of vegetation. Eggs, 2 to 4; incubation 25 d; young, ambulatory at hatching; time to fledging unknown. Swims. Flight "rapid, elegant, protracted" (Bent 1929).

Foraging. "Stands and watches," runs in pursuit of prey. Diurnal and nocturnal.

Prey/Food. Invertebrates: marine worms, small molluscs, shrimp, fiddler crabs, insects, etc.

Comments. Wintering, migrating, and nesting along beaches in the study area, numbers of this plover will be affected to a greater extent than many shorebirds by oiling of the beaches.

2. Oystercatchers [Family Haematopodidae]

American Oystercatcher - *Haematopus palliatus*
Florida Species of Special Concern (FGFWFC 1989)

Occurrence in Study Area. WR, PR, both very locally. Caxambus Pass, Marco Island, Keys and sand humps southwest of Cape Romano, Cape Sable, along Florida Bay Keys. CBCs, in three localities of the study area, 1977 to 1987 (11 years), recorded on only one occasion: a total of 2 birds.

Seasonality. Numbers increase slightly in fall, decrease in spring. A few present at all seasons, but breeding not yet known within the study area. Breeding elsewhere in Florida, March to June. According to T. Below (pers. comm. 1989), found on sand islets and reefs southwest of Marco Island; in winter, about 150; in summer, about 15.

Habitat/Natural History. Sandy beaches of bays, coasts, islands, sandy humps, mud flats, and mollusc beds at low tide. Small flocks, in winter; immatures under three years segregated from adults. Eggs, 2 to 3, deposited in sandy depression of high beach. Incubation, about 27 d; said to fly at 5 wk. Leave nest site at hatching and follow parents. Young fed by parents for long period. Swim well. Much resting (at high tides), while sitting or standing on one leg.

Foraging. Dependent on tidal cycle. Harvest raccoon oysters and clams as tide exposes them. Specialized techniques for extracting molluscs from shells.

Prey/Food. Molluscs, crustaceans (fiddler crabs), limpets, marine worms, etc.

Comments. The small and very localized population is at real hazard if mollusc beds are washed by oil. Oiled beaches where birds loaf, roost, and also forage, would be a serious threat.

3. Avocets and Stilts [Family Recurvirostridae]

American Avocet - *Recurvirostra americana*

Occurrence in Study Area. WV. Migrants from western states winter at Cape Sable area and at three extra-study-area sites in Florida; entire State population estimated at 500 (1970 to 1974) (DeGrange 1978). CBCs, 1977 to 1987, from Coot Bay-Everglades National Park, recorded avocets nine times: lowest count 5, highest 687, average 354 birds.

Seasonality. Arrives September to October, departs March to May. Not known to breed.

Habitat/Natural History. Prefers saline/alkaline areas to fresh water (Hamilton 1975), and shallow water over muddy/marl substrates, mudflats. When not foraging, much time resting, often on one leg. Highly social. Swims.

Foraging. Versatile; sexually dimorphic in bill shape. Bill specialized for gathering large numbers of small organisms from water or mud. Methods: "pecking," "snatching," "plunging," "bill pursuit," "filtering," "scraping," "single scything," "dabble scything" while "tipping" during swimming, and "multiple scything" (see Hamilton 1975). Foraging, both visual and tactile. Swinging of head and bill from side to side as in Roseate Spoonbill. Often forages in groups and cooperatively (Palmer 1968).

Prey/Food. Aquatic insects, their larvae, crustaceans, etc.

Comments. Varied foraging methods, many of them functional only while wading. Suggest this small concentrated wintering population is in jeopardy if the coastal environment is oil-polluted.

Black-necked Stilt - *Himantopus mexicanus*

Occurrence in Study Area. SR, WR rare. Mangrove areas, brackish, and freshwater areas inland. Entire southern and southwest rim of peninsula. Cape Sable. CBCs, from three localities in the study area, 1977 to 1987, recorded the species 15 times: average count 24 birds/recording, low count one, high count 106; only five recordings outside Coot Bay-Everglades National Park area.

Seasonality. February to October. Breeds April to June.

Habitat/Natural History. Freshwater wetlands; along the coast, shallow pools, mangrove lakes, shallow lagoons with muddy shores, brackish water marshes, and marine shores (Palmer 1968). Nests near water, usually near grasses or short growth. Nests on ground, sometimes with debris scraped into heap. Incubation, estimated 25 d; time to flying, 28 d (Palmer 1968).

Foraging. By wading or walking on muddy, marly substrates. Objects, frequently terrestrial insects, grabbed with jab of bill. Plunging entails reaching for prey at depth, head and neck in water. Snatching is employed with flying insects. (For foraging, see Hamilton 1975).

Prey/Food. Emphasis on insects, both terrestrial and aquatic; also small molluscs, crustaceans, worms, and fish.

Comments. Freshwater emphasis by a large part of this population mitigates hazards of oil pollution to this species.

4. Sandpipers and Allies [Family Scolopacidae:Scolopacinae]

Dunlin - *Calidris alpina*
(Red-backed Sandpiper; Black-bellied Sandpiper)

Occurrence in Study Area. WR, MV. CBCs, from three points within the study area, 1977 to 1987: average yearly total 2,775; maximum yearly total 5,360; minimum, 782.

Seasonality. Migration pulses, September to November and March to April; wintering birds and migrants, September to May.

Habitat/Natural History. Breeds on the tundra. In winter, beaches, tidal flats, exposed oyster reefs, margins of levees, etc. Page and Whitacre (1975) found this species to be the chief shorebird taken by avian predators during winter at a California lagoon.

Foraging. Usually in spread-out flocks moving briskly (Palmer 1968). Baker and Baker (1973) called Dunlins "generalists" in foraging.

Prey/Food. Small molluscs, small crustaceans, insects and their larvae, marine worms, seeds of aquatic plants, etc.

Comments. Habitat and foraging methods place this species at hazard in the event of oil-polluted intertidal zone.

Greater Yellowlegs - *Tringa melanoleuca*

Occurrence in Study Area. WR, MV. A few present all year. Shallow waters and mudflats along coasts of the mainland and Keys to the Dry Tortugas. Marshes, lagoons, and pools of the interior. CBCs, from three points within the study area, 1977 to 1987: average yearly total 98; maximum yearly total 222; minimum, 59.

Seasonality. Migration pulses, March to April and July to October; wintering birds and migrants, August to May.

Habitat/Natural History. Breeds on the tundra and muskeg. Migrants move to southern North America, the West Indies, and South America. Associates in small flocks of 10 to 20. Wary. Flight strong and rapid.

Foraging. Bill 50 to 65 mm. "Walks and wades" to belly, usually in small groups. Tilts body to "pick up" prey. Plows water surface, with mandibles agape. Swings bill from side to side through water. Runs after mobile prey.

Prey/Food. Invertebrates: molluscs, crustaceans, and insects. Small fish.

Comments. Threat to this species from oil-polluted waters is less than with species that winter in larger numbers and occur in flocks with greater numbers of individuals.

The **Lesser Yellowlegs** (*Tringa flavipes*), not considered here, is also present in the study area as a WR and MV. The two species commonly occur together in the same habitats. The Lesser usually occurs in larger flocks.

Least Sandpiper - *Calidris minutilla*

Occurrence in Study Area. WR, MV. Common on beaches and tidal flats all around Florida Bay, the Lower Keys, and the Southwest Florida coast. CBCs, 1977 to 1987, from three points within the study area: average yearly total 3,792; maximum yearly total 8,454; minimum, 322.

Seasonality. Migration pulses, July to October and April to May; wintering birds and migrants, July to May. A few, probably non-breeding birds, present all summer.

Habitat/Natural History. Breeds on the tundra near water. In winter, ocean beaches, intertidal areas, shores of ponds and lakes, and even flooded fields. Gregarious, often in flocks of mixed species.

Foraging. "Picks up" and "probes."

Prey/Food. Marine invertebrates: worms, molluscs, crustaceans, etc.

Comments. Oiled intertidal zones would result in heavy mortality of wintering and migrating birds.

Marbled Godwit - *Limosa fedoa*

Occurrence in Study Area. WR, MV. CBCs, 1977 to 1987, from Coot Bay-Everglades National Park area: average yearly total 102; maximum yearly total 390; minimum, 3. Fewer numbers recorded from Key Largo and Lower Keys, although 287 recorded on one count from Lower Keys.

Seasonality. Migration pulses, July to October and March to May; wintering birds and migrants, July to May.

Habitat/Natural History. Breeds on prairies of Canada and northern U.S. In winter, frequents mudflats, beaches, margins of lagoons, estuaries and bays (particularly oyster reefs at low tide), and tidal flats. Social, often in groups of a few to 40.

Foraging. One of the largest shorebirds, with a long bill (10 to 13 cm), probes in mud and on oyster reefs.

Prey/Food. Molluscs, crustaceans, worms, and other invertebrates.

Comments. This large bird, foraging on exposed tidal areas and in shallow water, would be at considerable hazard from oil-polluted littoral areas.

Red Knot - *Calidris canutus*

Occurrence in Study Area. WR, MV. A migrant and a winter resident. Beaches, particularly the intertidal zones, of the entire study area. CBCs, from three points within the study area, 1977 to 1987: average yearly total 58; maximum yearly total 117; minimum, 6.

Seasonality. Migration pulses from U.S. in general, July to October and April to May. Generally absent from North America from February to mid-March (Harrington 1986).

Habitat/Natural History. This, the largest of the true sandpipers, breeds in the central Canadian Arctic and winters in far southern South America. According to Harrington (1986), this is the longest bird-migration route known. Few stops are made en route; one segment 3,200- to 4,800-km long is accomplished in a non-stop flight.

Foraging. Usually in flocks; individuals closely spaced. These move at a rapid pace. Foraging birds step rapidly, then pause, probe several times in the sand or mud, and then move on again. Diurnal and nocturnal (Burger 1984).

Prey/Food. Invertebrates: worms, molluscs (*Donax* sp.), crustaceans, insects, etc.

Comments. Considerable numbers of knots (15,000 - see Harrington [1986]) winter coastwise between St. Petersburg and Naples, immediately north of the study area. It is not clear what proportion of this population may range to Marco Island beaches and beaches of the Southwest Florida coast. Nor is it clear as to how many migrants may stop in the study area en route to South America, although Florida is not a major stopping area (Harrington 1986). The Arctic nesting shorebirds most reduced in numbers are those that concentrate at "migration staging areas." Those birds that do pause here and those of the wintering concentration (one of a few in the U.S.) are certainly vulnerable to beach oiling. Ultimate effect on the North American breeding population of this species could be a considerable reduction in numbers.

Ruddy Turnstone - *Arenaria interpres*

Occurrence in Study Area. WR, MV, some immatures SR. CBCs, from three points within the study area, 1977 to 1987: average yearly total 319; maximum yearly total 549; minimum, 231. Larger numbers from the Lower Keys than from Upper Keys or Coot Bay-Everglades National Park. Immature birds may stay on wintering grounds their first summer.

Seasonality. Migration pulses, March to mid-April and August to September; wintering birds and migrants, August to April.

Habitat/Natural History. Breeds on the tundra and in varied boreal situations. Winters on or near the intertidal zone and on exposed flats with hard substrate.

Foraging. Food gathered from surface, pulled from sand, or exposed when pebbles and shells are overturned by bill. Occasionally digs holes while searching beaches. Usually in company with other turnstones and/or other species.

Prey/Food. Molluscs, crustaceans, worms, and other invertebrates.

Comments. Oil washing through intertidal zone will be hazardous to this species.

Sanderling - *Calidris alba*

Occurrence in Study Area. WR, MV. Difficult to estimate numbers passing during migration. CBCs, from three points within the study area, 1977 to 1987, a total of 1,792 individuals for an average yearly total of 54; maximum yearly totals: 462 and 446 at Coot Bay-Everglades National Park; minimum counts of 15 and 7; no birds on one count. At Naples (just north of the study area), and probably representative of Southwest Florida coast beaches, counts as high as 895 recorded.

Seasonality. Fall migrants, August to October; spring, March to May; wintering birds and migrants, August to May. Some non-breeding birds remain all summer (Palmer 1968).

Habitat/Natural History. Breeds High Arctic; of all shorebirds on coasts of North America, most widespread. Sandy beaches and shorelines. Imprinted to wintering sites to which individuals return (Myers 1988). Preyed upon by raptors (Page and Whitacre 1975).

Foraging. Along incoming or receding tide lines. Usually in flocks of ten or more. "Snatches and probes." Probing, by series of jabs. Picks up variety of food items washing ashore. Searches *Sargassum* washing ashore for prey.

Prey/Food. Principally, sandy-shore crustaceans, e.g. *Emerita* sp. (the mole crab) (Myers 1988). Also small molluscs, polychaete worms, amphipods, ostracods, etc.

Comments. According to Myers (1988), there has been a drop in population of 80% since 1972, while other shorebird species declined on the average of only 44%. Habitat protection looms as critical for this species. Chemical spills during migratory periods can be serious, and wintering populations can be severely reduced, the "traditions" of returning to specific wintering areas being compromised.

Semipalmated Sandpiper - *Calidris pusilla*

Occurrence in Study Area. WR, MV. Sandy beaches and tidal flats. CBCs, from three points within the study area, 1977 to 1987: average yearly total 167; maximum yearly total 837; minimum, zero. Morrison (1984) called this species the most numerous small sandpiper in eastern North America during migration; the species winters in northern South America. According to Morrison (1984), this species is one of several that migrate directly south from Atlantic coastal points north of Florida; in spring, this species takes a more westerly migration route northward and thus makes landfalls along southern coastlines of the U.S. These CBCs, of course, do not reflect spring abundances of this species in the study area.

Seasonality. Pulses of migration, July to October and April to May; wintering birds and migrants, July to May.

Habitat/Natural History. Breeds on the tundra. Winters along intertidal zone, and on mudflats and beaches.

Foraging. Snatches from surface and probes into soft substrates. Baker and Baker (1973) found that the most common foraging method on Florida Bay wintering grounds to be "pecking" and no "probing."

Prey/Food. Mostly aquatic insects and their larvae as well as small molluscs, crustaceans, and seeds.

Comments. Habitat and foraging methods place this species at hazard in the event of oil-polluted intertidal zone.

Short-billed Dowitcher - *Limnodromus griseus*

Occurrence in Study Area. WR, MV. Shorelines, tidal flats, and swamps of the mainland and Keys. Many migrants pass through to winter in the West Indies and South America. CBCs, from three points within the study area, 1977 to 1987: average yearly total 3,082; maximum yearly total 4,904; minimum 1,707. Among the most abundant wintering scolopacids.

Habitat/Natural History. Breeds on the tundra. In winter, shallow water within tidal areas or, less commonly, in freshwater wetlands. Muddy substrates preferred. As with many scolopacids, congregates at high tide to doze on the high beach, rocks, or debris. Very large flocks may gather at traditional stop-over places in migration.

Foraging. Bill, 50 to 70 mm. Probes in mud, sand, and drift-line seaweed. Wades. Follows dropping tidal water. Swims. May submerge head while probing.

Prey/Food. Invertebrates: worms, molluscs, crustaceans, insects and their larvae, etc.

Comment. Considering foraging--in flocks and probing while wading in shallow water at dropping tide--vulnerable to oil pollution along beaches and in estuaries. Large flocks at migration periods accentuate this vulnerability.

The **Long-billed Dowitcher** (*Limnodromus scolopaceus*), not considered here, also occurs in the study area as a WR and MV. It is said to prefer freshwater areas, whereas the Short-billed Dowitcher prefers brackish and marine areas. Both frequently occur together in either habitat. Some individuals are not easy to tell apart, and, therefore, field counts are not always accurate; in some CBC tallies, the two species are not differentiated, but are referred to as "Dowitcher sp." Such counts are not tallied in the CBCs given here, so these counts may be low.

Western Sandpiper - *Calidris mauri*

Occurrence in Study Area. WR, MV. Throughout the study area, on shorelines and tidal flats. CBCs, from three points within the study area, 1977 to 1987: average yearly total 3,405; maximum yearly total 19,102; minimum, 343. Of the three areas of counts, the Coot Bay-Everglades National Park count was in all 11 years, the largest of the three, a reflection of the areas of tidal flats there.

Seasonality. July to November and April to June. Wintering birds and migrants, July to June.

Habitat/Natural History. Breeds on coastal tundra of Alaska and northeast Siberia. Winters Pacific coast and the Atlantic coast from North Carolina southward to the West Indies and South America. Wintering habitat emphasizes mudflats, beaches, and, when inland, littoral areas, flooded agricultural lands, etc. With rising tides, these sandpipers rest in flocks at higher elevations of the beaches. Along with others of the smaller species, often feed on semi-flooded marl prairies west of Flamingo. There, dense flocks of these sandpipers, wheeling low over the landscape, are noteworthy.

Foraging. Feeds, in association with other small shorebirds, as the tide turns; the sandpipers follow the receding tidal line, in small to large flocks. Often feed with head in water. In Peru, Ashmole (1970) found that Western Sandpipers probed 70% of the time when in company with Semipalmated Sandpipers (which only probed on 21% of foraging bouts).

Prey/Food. Invertebrates: worms, molluscs, crustaceans, insects and their larvae, etc.

Comments. On the basis of CBCs, this is one of the most abundant small sandpipers wintering/migrating through the study area. Of all the smaller sandpipers, the Western, by virtue of its foraging along the receding tidal line, submerging its head and extracting food from the mud yet to be exposed, would be in real jeopardy in the event of oil-polluted foraging grounds. The large numbers of the birds emphasize serious consideration of this threat.

Willet - *Catoptrophorus semipalmatus*

Occurrence in Study Area. PR?, SR, WR, MV. Species continuously present. According to Palmer (1968), breeding birds of the southeastern U.S. depart after breeding, and northern migrants from western U.S. replace them; some pre-breeding birds of western U.S. populations remain all year. CBCs, 1977 to 1987, from the Coot Bay-Everglades National Park area, recorded Willets each year: average yearly total 1,313; maximum yearly total 3,288; minimum 1,111. Fewer numbers recorded from Key Largo and the Lower Keys.

Seasonality. Migration pulses, March to May and July to September. Breeding, April to June.

Habitat/Natural History. Sandy beaches, mudflats, and salt marshes. Swims readily. Nests semi-colonially. Nests in hollows amidst short, sparse vegetation, often in open areas or central hardpan of islands or Keys. Eggs, 3 or 4; incubation period, 22 d; young ambulatory at hatching; age to fledging not known.

Foraging. Bill lengths, to 5 cm. In salt or brackish waters. Often in intertidal zone. "Probes and snatches" while wading or walking on beach.

Prey/Food. Crustaceans (*Uca* sp., *Sesarma* sp.), snails (*Littorina* sp.), marine worms, insects, and small fishes (Howell 1932).

Comments. Intertidal habitat and considerable wading by this bird could jeopardize individuals in oil-polluted waters.

5. Gulls (non-pelagic) [Family Laridae:Larinae]

Bonaparte's Gull - *Larus philadelphia*

Occurrence in Study Area. WR; uncommon. CBCs, 1977 to 1987, from three points in the study area: a total of 73 birds for an average of <7/yr; maximum yearly total 19; one year, none recorded.

Seasonality. Fall arrival, September to November; spring departure, April to May; wintering birds, October to May.

Habitat/Natural History. Breeds in lowlands of North American taiga. In winter, frequents shorelines, bays, harbors, salt marshes, mudflats, inland freshwater ponds and lakes, and, on the seacoast, can be found on "waters well beyond the breakers" (Lowery 1974). Clapp et al. (1983) noted that some stay offshore for "extended periods." Gregarious. Swims buoyantly.

Foraging. Versatile: swims to food at surface, "picks" from mudflats. Forages along beaches. Wolf and Gill (1961) described a migrating group diving into the water (from 0.5 to 1.5 m above it), some birds completely submerging. King (1973) saw this gull "foot paddling" to stir up small organisms in tidal pools.

Prey/Food. In Florida, diet is: half fish; one-third insects; and the remainder, small snails, crustaceans, etc. (Howell 1932).

Comments. There are only small numbers in extreme southern Florida; their habits make them vulnerable to oil on water or beaches.

Herring Gull - *Larus argentatus*

Occurrence in Study Area. WR, MV. Throughout the study area. CBCs, 1977 to 1987, from three points in the study area: average yearly total 55; maximum yearly total 108; minimum, 27.

Seasonality. Fall migrations, October to November; spring, April to May; wintering birds and migrants, October to May. A few immatures may remain all summer.

Habitat/Natural History. Breeds from Alaska and Labrador south to South Carolina. In winter, in littoral areas and inshore waters. Gregarious with other species.

Foraging. Predator, scavenger, kleptoparasite. "Dipping to surface" and lands to take food; "surface-plunging" to shallow depths, plunging from as high as 7 m. Aerial pursuit of small birds and insects.

Prey/Food. Invertebrates and vertebrates, live and/or dead. Algae. Frequents garbage dumps.

Comments. Numbers reaching South Florida are small and are usually immature birds.

Laughing Gull - *Larus atricilla*

Occurrence in Study Area. SR, WR, MV, PR? Abundant year-round. Northern breeding birds move into South Florida in fall, many continue on to winter south of Florida; local birds disperse widely after breeding (Cramp et al. 1983). Breeds on Keys of both upper and lower Florida Bay, as many as 26 of such Keys utilized (Frohring and Kushlan 1986). CBCs, 1977 to 1988, from three points in the study area: average yearly total 3,926; maximum yearly total 8,012; minimum 1,084. Frohring and Kushlan (1986) reported 1,682 birds in Florida Bay at 19 nesting locations in 1982.

Seasonality. Nesting, March to August (Dinsmore and Schreiber 1974). Northward migration, mid-March to mid-May, northern birds found in Florida December to February (Cramp et al. 1983).

Habitat/Natural history. Coastal, inland waters irregularly. Nests in colonies (see Kushlan and White 1977b); nests on sand dunes, high sand bars, and salt marshes; in the study area, nests frequently in relatively open centers of mangrove islets; nests usually amidst scattered low herbage. Nests, of dried interwoven grasses, lined, sometimes placed beneath mangrove branches. Colony sites reused. Eggs, 3 to 4; incubation 20 d; young brooded at nest, and ambulatory after several days; time to fledging unknown. Calls of adults are a picturesque part of the coastal landscape.

Foraging. "Dips to surface" for fish. Follows ships for refuse. Inland, flocks follow ploughs and forage overturned soil for exposed invertebrates. Scavenges littoral areas. Feeds at garbage-disposal facilities.

Prey/Food. Chiefly fish, and a variety of scavenged animals and materials gleaned from refuse.

Comments. Because Laughing Gulls feed from the surface and rest upon the water, they are vulnerable to oiling. At times, the birds congregate (often in very large numbers) on sandbars in estuaries or offshore; here they loaf, roost, or wait for the tide to change; at these times, the birds would be extremely vulnerable to oil spills that wash ashore. When not breeding and confined to nesting-colony areas, gulls move over large areas and large flocks can gather; in the event of heavy mortality of fish, birds, etc. in the study area, scavenging gulls themselves could be affected. During nesting, oiled adults could oil both their eggs and young.

Ring-billed Gull - *Larus delawarensis*

Occurrence in Study Area. WR, MV. Throughout the study area. CBCs, 1977 to 1987, from three points in the study area: average yearly total 989; maximum yearly total 1,916; minimum, 437.

Seasonality. Fall arrivals, October to December. Peak numbers present January to February. Spring migration, February to early April. Some immature birds remain in summer. Present October to April.

Habitat/Natural History. Breeds mainly interior lowlands from boreal areas to the prairies, Canada and U.S. Coastal in the winter. Gregarious with own species and other gulls. Clement and Murphy (1987) reported 25,000 roosting on the ocean.

Foraging. As other gulls: picks from ground, from water's surface while swimming, or while hovering. Searches the coastlines from flight and lands to forage.

Prey/Food. Invertebrates, vertebrates, refuse, and garbage-dump materials.

Comments. In jeopardy from oil on water and beaches, as other gulls. Roosting assemblages afloat would incur extensive mortality from floating oil.

6. Terns [Family Laridae: Sterninae]

Arctic Tern - *Sterna paradisaea*

Occurrence in Study Area. MV, rare. This is an inter-hemispheric migrant which, in fall, passes offshore the east coast of Florida. Since 1952, a number of sight records have been made, as well as some specimens collected along the east coast, including one from Islamorada, Monroe County. There are now *fall* records from the Gulf coast (Wamer 1980).

Seasonality. Irregular fall and spring.

Habitat/Natural History. Breeds on Arctic tundra. Winters pelagically in Southern Hemisphere.

Foraging. "Plunge-dives."

Prey/Food. Unknown in Florida waters.

Comments. Oiling potential of no concern in the study area.

Black Noddy - *Anous minutus*

See discussions in Dry Tortugas and Pelagic Birds Sections of **Chapter 9**.

Occurrence in Study Area. SR. Dry Tortugas and surrounding ocean.

Black Tern - *Chlidonias niger*

Occurrence in Study Area. MV while en route between North American inland nesting grounds, and Central and South American wintering areas. Bulk of migrants appear to be trans-Gulf oriented and those of concern regarding the study area, more likely in western part. Buhrman and Hopkins (1978) reported 1,000+ on 25 September 1976, as well as scattered numbers on 8 May, 31 July, 27 August, and 17 September, and five groups on 10 October -- all more than 32 km (17.3 nmi) offshore Pinellas County.

Seasonality. Fall, July to November; spring, March to April.

Habitat/Natural History. Old and New World. When in migration, known to fly in very large flocks and roost on beaches in "close" ranks (Sprunt 1954).

Foraging. Most commonly "dips to surface," "plunge-diving" less commonly; only sometimes submerges head, occasionally body to wing tips. Aerial pursuit of insects. Gregarious at all seasons.

Prey/Food. During migration, fish and crustaceans, and insects where available.

Comments. Of concern: offshore oil during migration periods.

Bridled Tern - *Sterna anaethetus*

See also sections on Pelagic Birds and Dry Tortugas in **Chapter 9.**

Occurrence in Study Area. CV, particularly offshore Keys, including Tortugas, but sometimes enters inshore waters. After breeding, if not migratory, highly dispersive (Cramp et al. 1985). Nests abundantly on islands of Bahamas and Caribbean, including Cay Sal Bank; many of Florida Keys and Dry Tortugas birds probably come from the Cay Sal population.

Seasonality. Occurs at all seasons. University of Miami Reference Collections contain South Florida specimens from: April, May, August, September, and December.

Habitat/Natural History. Pan-tropical. Primarily offshore and *not* pelagic (Cramp et al. 1985), although regarded pelagic by many, e.g. Bond (1985).

Foraging. Chiefly from surface by "hovering and dipping." Follows schools of predatory fish for small fish they drive to surface. Active at night. Often in mixed-species flocks. When nesting, tends to forage in deep, offshore waters.

Prey/Food. Small fish and planktonic invertebrates, including crustaceans and molluscs.

Comments. Only scattered numbers of these birds would be endangered by an offshore oil spill; oil that might spread from the study area towards Cay Sal Bank, where terns breed and from which forage, a concern.

Brown Noddy - *Anous stolidus*

See discussions in Dry Tortugas and Pelagic Birds Sections of **Chapter 9.**

Occurrence in Study Area. SR. Dry Tortugas and surrounding ocean. Pelagic when not breeding.

Caspian Tern - *Sterna caspia*

Occurrence in Study Area. WR, probably MV. CBCs, 1977 to 1987, from three points in the study area for a total of 1,281: average yearly total about 116, maximum yearly total 167, minimum, 69; most numerous from Coot Bay-Everglades National Park. Probably occurs everywhere throughout the study area. Now known to nest as far south as Tampa area (Schreiber 1978b).

Seasonality. Arrivals in fall, October to December; departures, March to April; present in the study area, October to April.

Habitat/Natural History. Along the coastlines, bays, estuaries, and in freshwater wetlands. The largest tern, it has much similarity to gulls: in flight (soars), waddling walk, lurching run, swimming, etc. Associates with Royal Terns.

Foraging. Plunges for fish, swims and dives (even in rough water), "dips to surface," and occasionally feeds as does the Skimmer (Cramp et al. 1985). Robs other larids of prey.

Prey/Food. Mainly fish, including mullet (Howell 1932), and some invertebrates.

Comments. Concerns for this species mitigated by the relatively small wintering population present, but these birds will be in jeopardy if intertidal areas are washed with oil.

Common Tern - *Sterna hirundo*

Occurrence in Study Area. WR, MV. Stated to have nested on the Dry Tortugas; if so, this *was* the only nesting locality within the study area (Robertson 1964). From CBCs, Root (1988) reported an abundance peak between Tampa Bay to "below Naples." CBCs, 1977 to 1987, from three points within the study area: average yearly total 6; maximum yearly total 15; minimum, 2. Buhrman and Hopkins (1978) recorded 1,000+ on 25 September 1976, 42 km (22.6 nmi) west of Pinellas County; these were probably migrating birds which could be expected to pass through the study area. Fritts et al. (1983) reported that these terns migrate in numbers 15 to 30 km from shore and that they (or possibly Forster's Terns or other "common group terns") were present in numbers in December between the Dry Tortugas and Naples, Florida; the authors further suggested that these birds may be part of a "previously unrecognized concentration" of wintering birds.

Seasonality. WRs and MVs, from about September to May.

Habitat/Natural History. Old and New World; breeding in Arctic, boreal, temperate, and subtropical coastal and inland areas. Coastal areas in winter.

Foraging. Opportunistic in feeding (Cramp et al. 1985). Largely "plunge-diving" from 1- to 6-m heights; may hover, submergence partial or "dips to surface" for crustaceans and insects. Aerial pursuit of insects. Piracy of other sternids.

Prey/Food. Chiefly fish and crustaceans as well as insects.

Comments. Terns are vulnerable to oil in foraging areas and on beaches where they roost.

Forster's Tern - *Sterna forsteri*

Occurrence in Study Area. WR, MV. Throughout the study area. CBCs, 1977 to 1987, from three points within the study area: average yearly total 144; maximum yearly total 221; minimum, 22. See discussions of "common-group terns" above under the Common Tern.

Seasonality. Presence of WRs and MVs, July to May; but stragglers can be seen at any time of year (Howell 1932).

Habitat/Natural History. New World. Breeds largely inland. Migrates and winters along seacoasts. Frequents estuaries, Florida Bay, and area southwest of Marco Island.

Foraging. Adapted for insect-feeding, and flight features frequent turns and fast and shallow wingbeats. "Plunge-dives" and "dips to surface."

Prey/Food. Mainly fish and insects.

Comments. Vulnerable to oil.

Gull-billed Tern - *Sterna nilotica*

Occurrence in Study Area. Occasional WR, MV; SR not far north (central Florida) of study area. CBCs, 1977 to 1987, from three points within the study area, recorded the species only from the Coot Bay-Everglades National Park area for a total of 239: average yearly total about 21; maximum yearly total 64, minimum, zero (once). Individuals widely recorded: Dry Tortugas, Rebecca Shoals, etc.

Seasonality. Northward-bound migrants arrive about March 10 (Sprunt 1954), pass to the north of the study area, and begin their southward movement through the study area in August to September. Some birds present nearly year-round.

Habitat/Natural History. Lowland coasts, estuaries, lagoons, as well as inland lakes, rivers, and marshes. Less aquatic and less marine than most Sterninae (Cramp et al. 1985). Often only single birds, rarely more than two or three.

Foraging. Hawks for insects, "swoops" to take prey from ground or water's surface. Legs are longer than most terns, and walks and runs easily to pick up prey (Cramp et al. 1985). Most common fish-foraging by flying into wind, then "dipping to surface." Only occasionally "plunge-dives."

Prey/Food. Great diversity: fish, other vertebrates, and invertebrates (emphasizing insects and crustaceans).

Comments. Concern is minimal for the apparently small number of birds of the wintering population; however, what numbers of birds cross the study area during migration is not known.

Least Tern - *Sterna antillarum*
Florida Threatened (FGFWFC 1989)

Occurrence in Study Area. SR. Distributed around beaches and landfills, Upper and Lower Keys, Dry Tortugas, and inland freshwater areas. In 1989, 1,000+ nests southwest of Caxambus and on northwest Marco Island (T. Below, pers. comm. 1989). Hovis and Robson (1989) list sites of nesting survey along mainland Florida Keys, from 1 June to 1 July 1987; 37 Least Tern colonies on a total of 16 Keys, of these 59% were on dredge-material sites, and 38% on rooftops.

Seasonality. In spring, arrives March to April; in fall, departs September to October. Breeding, April to July.

Habitat/Natural History. Old World *S. albifrons* sometimes considered conspecific (AOU 1983). Nest, a scrape on vegetation-free substrate. Eggs, 2 to 3; incubation, 20 to 22 d; time to fledging, 28 d. Colonial in nesting. Where beaches inhospitable for nesting, now nests increasingly on gravel roofs.

Foraging. "Plunge-diving" by these birds a familiar sight along Florida beaches; hovers before diving; "dips to surface" for prey. Forages marine inshore waters and fresh water, and may fly several kilometers from nesting colony.

Prey/Food. Fish, shrimp, and many small invertebrates.

Comments. In the event of oil spills, special effort should be made to divert oil from beaches where these terns may be nesting.

Roseate Tern - *Sterna dougallii*
Florida Threatened, USFWS Threatened (FGFWFC 1989)

Occurrence in Study Area. WR small numbers, SR, MV. Breeds at Dry Tortugas and Lower Keys. Dry Tortugas, 250 to 300 pairs (Robertson 1978d); in 1989, probably 25 to 100 pairs, and small and irregular (W. Hoffman, pers. comm. 1989). In 1987, 300 pairs bred near Boca Chica Key; in 1988, bred on freshly bulldozed Key West harbour island which could be "biggest colony in eastern U.S." (W. Hoffman, pers. comm. 1989, National Audubon Society, Tavernier). CBCs, 1977 to 1987, from three points within the study area: average yearly total 6; maximum yearly total 40; minimum, zero (three times). All CBCs from Coot Bay-Everglades National Park.

Seasonality. SRs arrive April, depart September; nesting May to August. WRs and MVs from North Atlantic coast areas and/or Caribbean nesting population.

Habitat/Natural History. Old and New World. Buckley and Buckley (1981) estimated entire North American population at 2,500 pairs. Breeds along Atlantic coast from Nova Scotia to North Carolina and next southward, Florida, where very localized. Florida-breeding birds are part of the "Caribbean population" which is distinct from the Endangered northeastern North American population (Nisbet 1989).

Exclusively maritime, prefers shallow, sandy fishing grounds; shingle beaches with scattered herbage, sand dunes, sand spits, rock and sandy fill, and limestone shorelines. Nest on ground; often near debris or scattered plants. Eggs, 2; incubation period, 21 d; time to fledging, one month; continue to feed young after fledging.

Foraging. Largely "plunge-diving" into shallow and deep water; also "dips to surface"; hovers; follows schools of large fish which frighten smaller fish into jumping. Said to forage off reef edge of Boca Chica Key as well as edge of Upper Keys and into Gulf Stream (W. Hoffman, pers. comm. 1989).

Prey/Food. Entirely small fish (6- to 8-cm long) (Robertson 1978d).

Comments. The small study-area population, the only one in the U.S. south of North Carolina, could be jeopardized by any extensive "unnatural" mortality. Any considerable individual mortality would have long-range implications for the Florida population. Terns are vulnerable to oil over their foraging areas or on beaches where they nest, roost, etc.

Royal Tern - *Sterna maxima*

Occurrence in Study Area. MV, present year-round. Birds now nesting north of South Florida. Bred last century on Dry Tortugas and other South Florida localities; all sites abandoned early 1900s (Barbour 1978). Non-breeding birds now present on both coasts, along the Keys, and around Florida Bay in varying numbers all year. Re-establishing breeding colonies in north and central Florida (Barbour et al. 1976). CBCs, 1977 to 1987, from three points within the study area: average yearly total 679; maximum yearly total 1,039; minimum, 300. Hundreds sometimes attend shrimp-fishing boat activities only a few kilometers west of the Dry Tortugas.

Seasonality. Numbers in the study area greatest in non-breeding season, September to April. Numbers offshore Naples area and Southwest coast may represent southward migrants Caribbean-bound from northern Gulf colonies (Fritts et al. 1983).

Habitat/Natural History. Coastlines, particularly inlets between bays and ocean, sand islets, bars, mangrove coasts, inshore waters, and over and beyond the breakers. Sometimes encountered far from land; for example, Buhrman and Hopkins (1978) reported two 148 to 167 km (80 to 90 nmi) and two 154 km (83 nmi) due west of Pinellas County in February and April, respectively; and (Kale 1979b) reported hundreds 129 km (70 nmi) offshore Naples. Large flocks seen fall and winter. Roosts in groups on sand bars.

Foraging. Usually "plunge-dives" from 5 to 10 m, sometimes "aerial skims." Singly or in groups of two to three. Frequently follows schools of fish, fishing boats, and trawlers (Fritts et al. 1983). Frequently over shallow inshore waters. Forages up to 65 km from breeding colonies (Cramp et al. 1985). Foraging variables change with age and circumstances (Buckley and Buckley 1974).

Prey/Food. Mainly fish; some crustaceans, especially crabs.

Comments. There is reason for concern regarding any degree of unnatural mortality of a species which lays but one egg (Buckley and Buckley 1972), which continues parental feeding after fledging, "plunge-dives" for food, rests on the water, and is only now beginning to re-establish its numbers and range in Florida.

Sandwich Tern - *Sterna sandvicensis*

Occurrence in Study Area. WR, SR non-breeding, MV. Last century, bred along Keys, at Dry Tortugas, Cape Sable, and other coastal points, particularly Gulf coast. Much reduced early 1900s. Now breeds north of South Florida and in the Caribbean. Summer birds in the study area apparently dispersants from nesting areas. In winter, found from central Florida southward, some study-area birds probably MVs en route south. Occurrence throughout the study area, local and variable. CBCs, 1977 to 1987, from three points within the study area: average yearly total 25; maximum yearly total 73; minimum, 6. Root (1988) reported CBC peaks of abundance at Sarasota and Key West of 2.9 and 1.6 birds/party hour.

Seasonality. Present year-round; localization and irregularity of occurrence makes censusing difficult.

Habitat/Natural History. Old and New World. Northern populations move to warm waters after breeding; often migrate well offshore. Usually winters at inshore zone along coasts, in estuaries, at mud flats, mangrove-fringed shorelines, sandy beaches, etc. About sandbars, sand humps, following schools of predatory fish for smaller ones chased to surface; usually in company with gulls and other terns and roosts with flocks of these on sand bars, etc. Rarely swims.

Foraging. "Plunge-dives" from usually 5 to 10 m; sometimes hovers before "plunge-diving"; immersion usually just complete.

Prey/Food. Chiefly fish, occasionally shrimp.

Comments. As with other terns, oil hazardous.

Sooty Tern - *Sterna fuscata*

See discussions in Dry Tortugas and Pelagic Birds sections of **Chapter 9.**

Occurrence in Study Area. SR. Dry Tortugas and surrounding ocean. Pelagic when not breeding.

7. Skimmers [Family Laridae: Rynchopinae]

Black Skimmer - *Rynchops niger*

Occurrence in Study Area. PR, WR. Abundant in winter. In 1989, 150 nests on a sandbar south of Caxambus Pass (T. Below, pers. comm. 1989); possibly nests elsewhere in the study area. CBCs, 1977 to 1987, from three points within the study area: average yearly total 848; maximum yearly total 1,628; minimum, 310.

Seasonality. Numbers much augmented in winter. Northern migrants arrive September to October; depart March to April.

Habitat/Natural History. Beaches, sand bars, spoil islands, causeway shoulders, and parking lots (loafing and *roosting by day*). Gregarious.

Foraging. Largely nocturnal and crepuscular, but also by day. Lower mandible markedly longer than upper. Skims, whereby flies with lower mandible largely immersed, upper mandible over water and snapped shut when object encountered by lower. Known to wade into shallow water and grasp small fish (Howell 1932).

Prey/Food. Fish, crustaceans, and other marine invertebrates which may be close to the surface at night.

Comments. Foraging usually in relatively still waters of bays, estuaries, etc. If birds would skim oiled waters at night, local and wintering populations could be seriously affected.

PROFILES OF LAND BIRDS

A. The West Indian Avifaunal Element of the Study Area

Antillean Nighthawk - *Chordeiles gundlachii*

Occurrence in Study Area. SR. Key West, Lower and Upper Keys, and mainland locally to at least Homestead. Rare and localized (Robertson 1978g).

Seasonality. April to September, nesting within this period.

Habitat/Natural History. Open and semi-arid areas including landfills, scarified ground, etc. Nests on the ground. First found in Florida in 1942 (Greene 1946).

Foraging. In flight; "hawks" for insects.

Prey. Entirely insects.

Black-whiskered Vireo - *Vireo altiloquus*

Occurrence in Study Area. SR. Mangrove habitats throughout the study area. Nests.

Seasonality. April to September.

Habitat/Natural History. See Owre (1978b).

Foraging. Canopy gleaner.

Prey. Chiefly insects and their larvae.

Comments. This is one of the characteristic summer birds of the mangrove forests.

Cuban Yellow Warbler - *Dendroica petechia gundlachi*

Occurrence in Study Area. PR. Found from Key West to the mainland, and along the coast at least as far north as Miami (Robertson 1978h). CBCs, from three points within the study area, 1977 to 1978: average yearly total 12; maximum yearly total 19; minimum, 5. Since it is possible that northern subspecies of the Yellow Warbler may winter in southern Florida, it is not possible to state if these records are indeed of the Cuban Yellow Warbler.

Seasonality. Breeds January to July.

Habitat/Natural History. Almost entirely the fringing red mangrove swamps.

Foraging. Canopy feeder for insects.

Prey. Almost entirely insects.

Comments. The first Florida records were from the Lower Keys in 1941 (Greene 1946). The subspecies is actively extending its range northward.

Gray Kingbird - *Tyrannus dominicensis*

Occurrence in Study Area. SR. Found wherever there are scattered trees, particularly mangroves. Coastal situations favored. Nests.

Seasonality. April to September.

Habitat/Natural History. Abundant on the Keys and peninsular rim. Has spread northward into the peninsula and there entered quite different habitats: pineland, agricultural, suburban, etc. Perches on wires.

Foraging. Perches (exposed positions) and darts after insects.

Prey. Almost entirely insects.

Mangrove Cuckoo - *Coccyzus minor*

Occurrence in Study Area. PR. "...most common in the Lower Florida Keys, along the south coast of the mainland, and in the Ten Thousand Islands" (Robertson 1978f). Secretive and difficult to census.

Seasonality. Known egg dates 17 May to 10 July.

Habitat/Natural History. Not entirely restricted to the mangroves; also found in beach scrub, tropical hammock, etc. adjoining mangroves. In West Indies, less restricted to mangrove habitat. Nests: platforms of twigs in mangroves. Eggs, 2; incubation period and time to fledging unknown.

Foraging. Arboreal, gleans.

Prey. Caterpillars, many other insects, spiders, and some fruits.

Comments. Degradation of the mangrove habitat would certainly compromise activities of this species within the study area.

Mourning Dove - *Zenaida macroura macroura*

Mourning Doves range over much of U.S. south to Panama and the West Indies. *Z. m. carolinensis* is the breeding subspecies for eastern and southeastern U.S. including much of the Florida peninsula. On the Florida Keys, it is replaced by *Z. m. macroura*, the subspecies found in Cuba and the West Indies (Aldrich and Duvall 1958).

Occurrence in Study Area. PR. Reasonably abundant throughout the Keys and adjacent portions of the peninsula. CBCs, from three points within the study area, 1977 to 1987: average yearly total 134; maximum yearly total 171; minimum, 91. Mourning Doves of the northern subspecies winter in southern Florida; it is impossible to state whether these CBC counts are of the West Indian subspecies or the northern one since they cannot be reliably told apart in the field.

Seasonality. Breeds in many months of the year.

Habitat/Natural History. Common in open woodland and within cultivated lands with nearby scattered trees and bushes. Suburban areas.

Foraging. A ground-foraging, graminivorous bird.

Prey. Weed seeds and grains; minimal animal material.

Comments. Mourning Doves are foragers in upland areas and vulnerability to oil spills would seem remote; they would respond, however, to degradation of land areas.

Smooth-billed Ani - *Crotophaga ani*

Occurrence in Study Area. PR. CBCs, from three points within the study area, 1977 to 1987: average yearly total 16; maximum yearly total 38; minimum, zero (one time).

Habitat/Natural History. Varied habitats of the Keys, typically open areas with scattered growth, mangroves to some extent. First records and nestings in Florida in the 1930s (Sprunt 1954). Now throughout Keys and lower portion of Florida peninsula. Lives in flocks and nests communally.

Foraging. Forages in loose flocks, commonly on ground.

Prey. Grasshoppers, lizards, etc.

Comments. Common in South America and the West Indies, this Ani has been a successful colonizer. Its appearance, social life, and unusual nesting habits (Loflin 1983) make it an exceedingly interesting member of the terrestrial avifauna.

White-crowned Pigeon - *Columba leucocephala*
Florida Threatened, USFWS Under Review 2 (FGFWFC 1989)

Occurrence in Study Area. PR, SR. Breeds on mangrove islets along the extent of the Florida Keys to the Marquesas, throughout Florida Bay, and along the southern rim of the peninsula. A portion of the breeding population migrates to winter in Cuba, the Bahamas, and other Caribbean islands where others of the species nest. Forages in open forest and other habitats of the Keys and mainland. CBCs, 1977 to 1987, from three points within the study area: average yearly total 87; maximum yearly total 139;

minimum, 50. Note: the CBC data reflect only the wintering population of this species which is largely a SR.

Seasonality. Spring arrivals irregular: April to May; fall departures not well documented, about August to October; breeds May to about August.

Habitat/Natural History. Major range of this tropical columbid is the islands of the Caribbean; Florida is the only mainland portion of its range. Colonial in nesting. Nests in mangroves, one nest/tree. Eggs, 1 to 2; incubation, about 14 d; time to fledging, about 21 d (Wiley and Wiley 1979). May have two broods. Roosts communally.

Foraging. Frugivorous, arboreal; gleans. In Florida, conspicuous in early morning and during evening flights to and from mangrove islets and foraging situations of higher ground.

Prey/Food. A large variety of fruits and berries (e.g., of strangler fig *Ficus aurea*, poisonwood *Metopium toxiferum*, cocoplum *Chrysobalanus icaco*, Royal Palm *Roystonia* sp., etc); also snails and small insects.

Comments. The White-crowned Pigeon is a unique component of the mangrove ecosystem (Owre 1978a). Elsewhere in its range, the species has experienced drastic declines in numbers and has been extirpated from some islands (Wiley and Wiley 1979). Florida is one of few places where adults and squabs are not hunted. Long-term damage to and/or disturbance within large areas of the red mangroves would be serious for this population.

B. Endemic Subspecies of the Study Area

Cape Sable Seaside Sparrow - *Ammodramus maritimus mirabilis*
Florida Endangered, USFWS Endangered (FGFWFC 1989)

Occurrence in Study Area. PR. Range of this endangered subspecies formerly restricted to four areas within extreme southern Florida. The Cape Sable range within the cordgrass (*Spartina bakeri*) marsh stretched from Flamingo to northwest Cape Sable and is now unoccupied or nearly so (Kushlan and Bass 1983b) as is the Ochopee-Carnestown range. The remaining areas of its range are inland from the coast: East Everglades, Taylor's Slough, and Big Cypress National Preserve. Remaining population in 1981 was 6,600 birds (Kushlan and Bass 1983b).

Seasonality. Breeds February to August.

Habitat/Natural History. This "seaside" sparrow now inhabits freshwater marshes dominated by muhly grass (*Muhlenbergia* sp.). Nest, a cup or dome of fibers suspended within a grass tussock (Werner 1978). Eggs, 3 to 4; incubation, 11+ d; leaves nest as "pedestrian"; flies 10 to 20 d later.

Foraging. On ground.

Prey. Insects, spiders, worms, small snails, etc.

Comments. Present inland habitats would seem to render it sufficiently removed from the dangers of floating spills.

Prairie Warbler - *Dendroica discolor paludicola*

Occurrence in Study Area. PR, some probably only SR. Found in mangroves everywhere within the study area. CBCs, from three points within the study area, 1977 to 1987: average yearly total 194: maximum yearly total 364; minimum, 92. It is not known to what extent the northern subspecies (*D. d. discolor*) winters in extreme southern Florida. The endemic subspecies (*D. d. paludicola*) is probably sedentary, but these counts cannot be assumed to be entirely those of the endemic individuals.

Seasonality. Breeds February to July. In winter, some migrate to the West Indies (Stevenson 1978). Birds of the northern subspecies migrate through the study area and some may winter.

Habitat/Natural History. Almost entirely restricted to mangroves when breeding. Nests are in mangroves, and of plant fibers. Eggs, 3 to 5; incubation, 12 to 14 d; young fledge 8 to 10 d.

Foraging. Gleans through the canopy for insects.

Prey. Insects and small invertebrates.

Comments. The birds of this ecological race derive their energy from the insect and invertebrate fauna produced by the mangrove habitat. Degradation of this habitat could affect this unique subspecies.

C. Migrants That Pass Through the Study Area in Spring and/or Fall

Barn Swallow - *Hirundo rustica*

Occurrence in Study Area. MV, very uncommon WR. CBCs, 1977 to 1987, recorded Barn Swallows on eight occasions for a total of 31 birds from the Coot Bay-Everglades National Park area and five from the Lower Keys. One of the abundant spring and fall migrants through the peninsula and the study area, the Dry Tortugas included.

Seasonality. July to October; April to May.

Habitat/Natural History. The swallows fly low, coursing over the canopy, ground, and water. Hundreds may pass by during a day and their passage continues for weeks during the fall; for a shorter period in the spring. Numbers may roost in close ranks on utility wires and dead trees.

Foraging. As they migrate, swallows forage for insects.

Prey. Almost entirely flying insects.

Comments. The insect fauna of the study area is important, energetically speaking, to the migration of this species.

Blackpoll Warbler - *Dendroica striata*

Occurrence in Study Area. MV. The Florida peninsula is a major *spring* Flyway of this warbler en route from South America (Lincoln 1939).

Seasonality. April to May; to some extent, September to October.

Habitat/Natural History. In migration, forests including mangroves and tropical hammocks.

Foraging. Searches leaves and blossoms for insects.

Prey/Food. Insects and other small invertebrates.

Comments. In spring, a large portion of the population of this species may forage through the arboreal habitats of South Florida.

Bobolink - *Dolichonyx oryzivorus*

Occurrence in Study Area. MV. Large numbers pass over and/or through the study area en route to and from South America.

Seasonality. April to May; August to October.

Habitat/Natural History. Birds of prairies and grasslands. During spring, this writer has seen flocks of sometimes many hundreds pause on open ground, lawns, roadsides, etc. at the Dry Tortugas, Pigeon Key, Cape Sable, Marco Island, etc. Here, they were gleaning seeds and insects.

Foraging. Specialized to feed on the ground where it hunts/gleans for food.

Prey/Food. Largely seeds, to some extent insects.

Comments. Numbers of this species are, at times, dependent upon plant and insect productivity of the study area for continuance of their migration.

Cape May Warbler - *Dendroica tigrina*

Occurrence in Study Area. MV, uncommon WR. One of the most abundant warbler migrants in both spring and fall. Woodland habitats including mangroves and tropical hammock. CBCs, from three points within the study area, 1977 to 1987: average yearly total 5; maximum yearly total 20, minimum, 1; these data emphasize that small numbers of this warbler winter here.

Seasonality. March to April; September to November.

Habitat/Natural History. Breeds in the coniferous forests of the Boreal Zone and winters in the West Indies. It is mostly a bird of the canopy.

Foraging. Searches leaves and blossoms for insects.

Prey. Insects and small berries.

D. Land Birds That Only Winter in the Study Area

Belted Kingfisher - *Ceryle alcyon*

Some species of kingfishers are atypical land birds in that they forage within aquatic situations for their food.

Occurrence in Study Area. WR, MV. Is found wherever still, clear water occurs along the mangrove coast, Keys to the Marquesas, islets of Florida Bay, the Southwest Florida coast, and brackish and freshwater areas inland. Dry Tortugas, at least in migration. CBCs, 1977 to 1987, from three points in the study area: average yearly total 140; maximum yearly total 167; minimum, 109.

Seasonality. Fall arrivals, August to November; spring departures, March to May. Wintering birds, probably August to May. MVs to and from West Indies.

Habitat/Natural History. Virtually wherever there are water and suitable perches. Does not nest in southern Florida, although Howell (1932) gives a record from Flamingo--such cannot be widespread. Roosts on perches near water. Noisy.

Foraging. "Plunge-dives," often hovering first. Only head in water or complete submergence. Requires clear, relatively still water. Uses perches such as dead branches, posts, wires, etc. from which to sight prey. Solitary and territorial.

Prey. Largely fish, also small snakes, turtles and other vertebrates; crustaceans, insects; along coasts, known to take clams and oysters (Terres 1980). Disgorges indigestible material as pellets.

Comments. Because they require clear water for sighting prey, kingfishers might not forage in oil-covered water. Any lingering oil, however, would "dislocate" birds from what may well be "traditional" wintering territories.

Blue-gray Gnatcatcher - *Polioptila caerulea*

Occurrence in Study Area. WR, some MV. Common peninsular rim; Keys to the Marquesas. CBCs, 1977 to 1987, from three points in the study area: average yearly total 513; maximum yearly total 869; minimum, 269.

Seasonality. July to April.

Habitat/Natural History. Tropical hammocks, mangrove forests, and suburban yard trees.

Foraging. Gleans leaves and "flycatches." Very active.

Prey. Beetles, ants, flies, gnats, and insect eggs and larvae.

Palm Warbler - *Dendroica palmarum*

Occurrence in Study Area. WR, MV. Wherever there is open ground, either upland or beaches. CBCs, 1977 to 1987, from three points in the study area: average yearly total 366; maximum yearly total 610; minimum, 206.

Seasonality. Present September to May; migration pulses, September to November and March to May.

Habitat/Natural History. Largely terrestrial. "Flycatches" and "plucks" food from all types of open areas.

Foraging. Almost exclusively on the ground, rarely from branches. Partial to roadside shoulders, pastures, city parks, *littoral drift lines, and beaches*.

Prey. Insects, ants, and spiders.

Comments. One of the commonest wintering species in Florida (Griscom and Sprunt 1957).

Tree Swallow - *Tachycineta bicolor*

Occurrence in Study Area. WR. Land areas of the peninsular rim; less common on the Keys. CBCs, 1977 to 1987, from Coot Bay-Everglades National Park: average yearly total 1,586; maximum yearly total 14,647; minimum, 3.

Seasonality. August to May.

Habitat/Natural History. This swallow can winter in North America because it shifts its diet from insects to fruit (in winter).

Foraging. Moves across the landscape in loose flocks; dense aggregations swarm around trees with fruit that is being harvested.

Prey. Flying insects; in winter, feeds on fruits of wax myrtle, Virginia creeper, and other native plants.

Yellow-bellied Sapsucker - *Sphyrapicus varius*

Occurrence in Study Area. WR, some MV. Keys and the mainland rim. CBCs, from three points within the study area, 1977 to 1987: average yearly total 9; maximum yearly total 17; minimum, 4.

Seasonality. October to May.

Habitat/Natural History. Breeds in the boreal-hardwood forests of much of northern North America. In winter, frequents mangroves, tropical hammocks, and other tree growths.

Foraging. Sapsuckers carve holes in the bark of trees and shrubs and feed upon the phloem sap and insects attracted to it.

Prey. Sap, bast (phloem tissue), insects, and, less commonly, fruit.

Comments. Old sapwells on tree trunks in the study area attest to the productivity of the trees in sustaining winter populations of these birds.

E. Permanent Residents Common to Southeastern U.S. and South Florida

Burrowing Owl - *Athene cunicularia*
Florida Species of Special Concern (FGFWFC 1989)

Occurrence in Study Area. PR. Present locally on the Keys (Sprunt 1954). Individuals must wander here during post-breeding dispersal (Owre 1978c). CBCs, from three points within the study area, 1977 to 1987, recorded the Burrowing Owl only once. This is probably a reflection of the fact that the birds are highly local in occurrence.

Seasonality. Nests November to May.

Habitat/Natural History. Open ground including: vacant lots, landfills, pastures, wide road shoulders, etc. Nesting: a burrow in the ground usually dug by the owls. Eggs, 7 to 9; incubation, 28 d; age to fledging?

Foraging. Crepuscular, nocturnal, and to some extent, diurnal. Watches from a prominence (mounds, fence posts, etc.). Makes short flights close to the ground.

Prey. Insects, lizards, small birds, and mammals.

Red-bellied Woodpecker - *Melanerpes carolinus*

Occurrence in Study Area. PR. Upland woodlands, tropical hammocks, mangroves, Keys, islets, etc. CBCs, from three points in the study area, 1977 to 1987: average yearly total 66, maximum yearly total 97; minimum, 45.

Seasonality. Breeds February to July; multiple brooded.

Habitat/Natural History. Almost any sparsely or densely wooded area, including urban/suburban parks, yards. Moves back and forth from neighboring woodlands and mangroves. Cavity nester. Eggs, 4 to 5; incubation 11 d; time to fledging about 25 d; follows parents for about 6 wk.

Foraging. Searches tree trunks, excavates for insect larvae, ants, termites, etc. Gleans fruit/berries.

Prey. Insects and much plant material including fruits and berries. In mangroves, tunnels for termites *Prorhinotermes simplex* and *Neotermes* sp. which both have a high tolerance for salinity.

Comments. This woodpecker is an integral part of the mangrove community and other study area woodlands.

Red-winged Blackbird - *Agelaius phoeniceus*

Occurrence in Study Area. PR. Marsh and swampy habitats of virtually all land areas of the mainland rim and the Keys to the Marquesas. CBCs, from three points in the study area, 1977 to 1987: average yearly total 1,726; maximum yearly total 2,893; minimum, 967.

Seasonality. Nesting May to July.

Habitat/Natural History. Marshes and swampy habitats as well as pastures, lawns, and open ground. Nests in dwarf mangroves, buttonwoods, bushes, etc. Eggs, 3 to 5; incubation, 11 d; leaves nest at 10 d by climbing from it. Double-brooded. Nesting approximately coincides with onset of rainy season and with increasing numbers of insects (particularly aquatic insects), important as food for young.

Foraging. Hunts through cattails and other aquatic growth as well as bushes of marsh areas. In winter, sexually segregated flocks often forage on the ground and roost in trees.

Prey/Food. Aquatic insects (their larvae in particular). In winter, weed seeds and grains.

White-eyed Vireo - *Vireo griseus*

Occurrence in Study Area. PR, some MV. Generally distributed over the landmasses of the study area; present throughout the year. CBCs, from three points within the study area, 1977 to 1987: average yearly total 78; maximum yearly total 113; minimum, 36.

Seasonality. Migration pulses, March to May and September to November; breeding, February to July.

Habitat/Natural History. A bird of the thickets and bushes of the understory. Nest of fibers, three to five feet above ground in a bush. Eggs, 3 to 5; incubation, 12 to 15 d; age at fledging?

Foraging. In bushes and thickets; never far from ground. Hunts methodically.

Prey/Food. Insects and small invertebrates; some fruit in fall and winter, e.g., wax myrtle.

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REFERENCES CITED

Aldrich, J. W., and A. J. Duvall. 1958. Distribution and migration of races of the Mourning Dove. *Condor* 60:108-128.

Allen, R. P. 1942. *The Roseate Spoonbill.* Res. Rep. No. 2, Natl. Audubon Soc. New York: National Audubon Society.

American Ornithologists' Union. 1983. *Check-list of North American birds, 6th Ed.* Lawrence: Allen Press, Inc.

Arbib, R. S., Jr. 1977. The seventy-seventh Audubon Christmas bird count. *Am. Birds.* Vol. 31.

Arbib, R. S., Jr. 1978. The seventy-eighth Audubon Christmas bird count. *Am. Birds.* Vol. 32.

Arbib, R. S., Jr. 1979. The seventy-ninth Audubon Christmas bird count. *Am. Birds.* Vol. 33.

Arbib, R. S., Jr. 1980. The eightieth Audubon Christmas bird count. *Am. Birds.* Vol. 34.

Arbib, R. S., Jr. 1981. The eighty-first Audubon Christmas bird count. *Am. Birds.* Vol. 35.

Arbib, R. S., Jr. 1982. The eighty-second Audubon Christmas bird count. *Am. Birds.* Vol. 36.

Arbib, R. S., Jr. 1983. The eighty-third Audubon Christmas bird count. *Am. Birds.* Vol. 37.

Arendt, W. J. 1988. Range expansion of the Cattle Egret (*Bubulcus ibis*) in the greater Caribbean Basin. *Colonial Waterbirds* 11(2):252-262.

Ashmole, M. J. 1970. Feeding of Western and Semipalmated Sandpipers in Peruvian winter quarters. *Auk* 87:131-135.

Ashmole, N. P. 1971. Sea bird ecology and the marine environment. In *Avian Biology, Vol. 1*, ed. D. S. Farmer and J. R. King, 223-286. New York: Academic.

Atherton, L. 1981. Florida region. *Am. Birds* 35:173.

Baker, M. C., and E. M. Baker. 1973. Niche relationships among six species of shorebirds on their wintering and breeding ranges. *Ecol. Monogr.* 43:193-212.

Barbour, D. B. 1978. Royal Tern. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 91-92. Gainesville: Univ. Presses of Fla.

Barbour, D. B., S. A. Nesbitt, and D. H. Gilbert. 1976. A second recent Royal Tern nesting colony on the Gulf Coast of Florida. *Fla. Field Natur.* 4:9-10.
Bass, O. L., Jr., and L. C. McEwan. 1978. *Status of colonial birds in south Florida national parks, January-March 1978.* Report prepared for the Everglades National Park.
Bellrose, F. C. 1980. *Ducks, geese and swans of North America.* Harrisburg: Stackpole Books.
Bent, A. C. 1919. *Life histories of North American diving birds.* U.S. Natl. Mus. Bull. No. 107.
Bent, A. C. 1923. *Life histories of North American wild fowl.* U.S. Natl. Mus. Bull. No. 126.
Bent, A. C. 1929. *Life histories of North American shorebirds.* U.S. Natl. Mus. Bull. No. 146.
Bent, A. C. 1937. *Life histories of North American birds of prey.* U.S. Natl. Mus. Bull. No. 167.
Black, B. B., and M. W. Collopy. 1982. Nocturnal activity of Great Blue Herons in a North Florida salt marsh. *J. Field Ornithology* 53:403-406.
Bond, J. 1985. *Birds of the West Indies, 5th Ed.* Boston: Houghton Mifflin.
Bowman, R., and G. T. Bancroft. 1989. Least Bittern nesting on mangrove keys in Florida Bay. *Fla. Field Natur.* 17:43-46.
Bowman, R., J. Hovis, N. C. Kline, G. V. N. Powell, and T. Wilmers. 1987. Variations in reproductive success between subpopulations of the Osprey (*Pandion haliaetus*) in south Florida. Vol. 3. In *A symposium on Florida Bay, a subtropical lagoon, Program and Abstracts.*
Brown, L., and D. Amadon. 1968. *Eagles, hawks and falcons of the world, Vol. 1.* New York: McGraw-Hill Book Co.
Buckley, F. G., and P. A. Buckley. 1972. The breeding ecology of Royal Terns *Sterna (Thalasseus) maxima maxima. Ibis* 114:344-359.
Buckley, F. G., and P. A. Buckley. 1974. Feeding ecology of Royal Terns. *Ecology* 55:1053-1063.
Buckley, F. G., and P. A. Buckley. 1981. The endangered status of North American Roseate Terns. *Colonial Waterbirds* 4:166-173.
Buhrman, C. B., and L. A. Hopkins. 1978. Eleven pelagic trips into the eastern Gulf of Mexico. *Fla. Field Natur.* 6:30-32.
Burger, J. 1984. Shorebirds as marine animals. In *Shorebirds, breeding behavior and populations, behavior of marine animals, Vol. 5,* ed. J. Burger and B. L. Olla, 17-81. New York: Plenum Press.
Burger, J., L. M. Miller, and D. C. Hahn. 1978. Behavior and sex roles of nesting Anhingas at San Blas, Mexico. *Wilson Bull.* 90:359-375.
Byrd, M. A. 1978. Dispersal and movements of six North American Ciconiiformes. In *Wading birds,* ed. A. Sprunt IV, J. C. Ogden, and S. Winckler, 161-185. New York: National Audubon Society Research Rep. 7.
Cade, T. J. 1982. *The falcons of the world.* Ithica: Cornell Univ. Press.
Chapman, J. D., and W. F. Loftus. 1986. American White Pelican feeding in freshwater marshes of the Everglades National Park, Florida. *Fla. Field Natur.* 15:20-21.
Clapp, R. B., R. C. Banks, D. Morgan-Jacobs, and W. A. Hoffman. 1982a. *Marine birds of the southeastern United States and Gulf of Mexico. Part. I. Gaviiformes through Pelecaniformes.* FWS/OBS-82/01. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.
Clapp, R. B., D. Morgan-Jacobs, and R. C. Banks. 1982b. *Marine birds of the southeastern United States and Gulf of Mexico. Part. II. Anseriformes.* FWS/OBS-82/20. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.
Clapp, R. B., D. Morgan-Jacobs, and R. C. Banks. 1983. *Marine birds of the southeastern United States and Gulf of Mexico. Part. III. Charadriiformes.* FWS/OBS-83/30. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.
Clement, T. C., and T. (V.) Murphy. 1987. Ring-billed Gulls roost on ocean. *Fla. Field Natur.* 15:82.
Craig, G. 1986. Peregrine Falcon. In *Audubon wildlife report, 1986,* ed. R. Di Silvestro, 806-824. New York: National Audubon Society.
Cramp, S., K. E. L. Simmons, I. J. Ferguson-Lees, R. Gillmor, P. A. D. Hollom, R. Hudson, E. M. Nicholson, M. A. Ogilvie, P. J. S. Olney, K. H. Voous, and J. Wattel, ed. 1977. *Handbook of the birds of Europe, the Middle East and North Africa. Vol. 1.* Oxford: Oxford Univ. Press.
Cramp, S., K. E. L. Simmons, R. Gillmor, P. A. D. Hollom, R. Hudson, E. M. Nicholson, M. A. Ogilvie, P. J. S. Olney, C. S. Roselaar, K. H. Voous, D. I. M. Wallace, and J. Wattel, ed. 1980. *Handbook of the birds of Europe, the Middle East and North Africa. Vol. 2.* Oxford: Oxford Univ. Press.
Cramp, S., K. E. L. Simmons, D. J. Brooks, N. J. Collar, E. Dunn, R. Gillmor, P. A. D. Hollom, R. Hudson, E. M. Nicholson, M. A. Ogilvie, P. J. S. Olney, C. S. Roselaar, K. H. Voous, D. I. M. Wallace, J. Wattel, and M.G. Wilson, ed. 1983. *Handbook of the birds of Europe, the Middle East and North Africa. Vol. 3.* Oxford: Oxford Univ. Press.
Cramp, S., D. J. Brooks, E. Dunn, R. Gillmor, P. A. D. Hollom, R. Hudson, E. M. Nicholson, M. A. Ogilvie, P. J. S. Olney, C. S. Roselaar, K. E. L. Simmons, K. H. Voous, D. I. M. Wallace, J. Wattel, and M.G. Wilson, ed. 1985. *Handbook of the birds of Europe, the Middle East and North Africa. Vol. 4.* Oxford: Oxford Univ. Press.
Cummings, M. V. 1987. The feeding energetics of the Double-crested Cormorant in Biscayne Bay, Florida. Ph.D. diss., Univ. of Miami.
Darrow, H. N. 1982. Late fall movements of Turkey Vultures and hawks in the Florida Keys. *Fla. Field Natur.* 11:35-40.
DeGrange, A. K. 1978. American Avocet. In *Rare and endangered biota of Florida,* ed. H. W. Kale II, 88-89. Gainesville: Univ. Presses of Fla.
Dinsmore, J. J., and R. W. Schreiber. 1974. Breeding and annual cycle of Laughing Gulls in Tampa Bay, Florida. *Wilson Bull.* 86:419-427.
Drennan, S. R. 1986. The eighty-sixth Audubon Christmas bird count. *Am. Birds.* Vol. 40.
Drennan, S. R. 1987. The eighty-seventh Audubon Christmas bird count. *Am. Birds.* Vol. 41.
Dunstan, F. M. 1978a. Black-crowned Night Heron. In *Rare and endangered biota of Florida,* ed. H. W. Kale II, 78-79. Gainesville: Univ. Presses of Fla.
Dunstan, F. M. 1978b. Glossy Ibis. In *Rare and endangered biota of Florida,* ed. H. W. Kale II, 82-83. Gainesville: Univ. Presses of Fla.
Eagan, T. 1989. Lawsuits snarl study of imperiled Alaskan eagles. *New York Times.* Sept. 19:21-22.
Farrand, J., Jr. 1984. The eighty-fourth Audubon Christmas bird count. *Am. Birds.* Vol. 38.
Farrand, J., Jr. 1985. The eighty-fifth Audubon Christmas bird count. *Am. Birds.* Vol. 39.
Fleming, D. A., and N. C. Kline. 1987. A comparison of Osprey nesting distribution, abundance, and success in Florida Bay from 1968 to 1984. In *A symposium on Florida Bay, a subtropical lagoon, Program and Abstracts,* 1-5.

Florida Game and Fresh Water Fish Commission. 1989. *Official list of endangered and potentially endangered flora and fauna in Florida*. Tallahassee: Florida Game and Fresh Water Fish Commission.
Frederick, P. C., and M. W. Collopy. 1988. *Reproductive ecology of wading birds in relation to water conditions in the Florida Everglades*. Florida Cooperative Fish and Wildlife Research Unit, School for Research and Conservation, Univ. Fla. Tech. Rep. No. 30.
Fritts, T. H., A. B. Irvine, R. D. Jennings, L. A. Collum, W. Hoffman, and M. A. McGehee. 1983. *Turtles, birds and mammals in the northern Gulf of Mexico and nearby Atlantic waters*. FWS/OBS-82/65. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.
Frohring, P. C., and J. A. Kushlan. 1986. Nesting status and colony site variability of Laughing Gulls in southern Florida. *Fla. Field Natur.* 14:1-16.
Gaby, S. R. P. 1982. Age-specific resource utilization by wintering migrant Turkey Vultures (*Cathartes aura*) in south Florida. Ph.D. diss., Univ. of Miami.
Green, N. 1985. The Bald Eagle. In *Audubon wildlife report 1985*, ed. R. Di Silvestro, 508-531. New York: National Audubon Society.
Greene, E. R. 1946. Birds of the Lower Florida Keys. *Q. J. Fla. Acad. Sci.* 8(3):199-265.
Griscom, L., and A. Sprunt, Jr. 1957. *The warblers of America*. New York: Devin-Adair, Co.
Gusey, W. P., ed. 1981. *The fish and wildlife off the south Atlantic coast*. Houston: Shell Oil Co.
Haig, S. M., and L. W. Oring. 1987. The Piping Plover. In *Audubon wildlife report 1987*, ed. R. L. Di Silvestro, 508-519. New York: Academic Press.
Hamilton, R. B. 1975. Comparative behavior of the American Avocet and the Black-necked Stilt (Recurvirostridae). *Ornithol. Monogr.* Vol. 17. American Ornithologists' Union.
Hancock, J., and J. Kushlan. 1984. *The herons handbook*. New York: Harper & Row.
Harrington, B. A. 1986. The Red Knot. In *Audubon wildlife report 1985*, ed. R. Di Silvestro, 871-886. New York: National Audubon Society.
Harrington, B. A., R. W. Schreiber, and G. E. Woolfenden. 1972. The distribution of male and female Magnificent Frigatebirds, *Fregata magnificens*, along the Gulf coast of Florida. *Am. Birds* 26:927-931.
Hovis, J. A., and M. S. Robson. 1989. Breeding status and distribution of the Least Tern in the Florida Keys. *Fla. Field Natur.* 17:61.
Howell, A. H. 1932. *Florida bird life*. New York: Coward-McCann, Inc.
Hundley, M. H., and F. Hames. 1960. Bird life of the lower Florida Keys. *Fla. Natur.* 33:209-214.
James, D. A., and J. C. Neal. 1986. *Arkansas birds*. Fayetteville: Arkansas Press.
Kale, H. W. II. 1978. Florida Clapper Rail. In *Rare and endangered biota of Florida, Vol. 2*, ed. H. W. Kale II, 112-113. Gainesville: Univ. Presses of Fla.
Kale, H. W. II. 1979a. *Data on selected groups of birds on the Atlantic coast of Florida*. Report prepared for Shell Oil Company, Environmental Affairs. Maitland: Florida Audubon Society.
Kale, H. W. II. 1979b. *Data on selected groups of birds on the Gulf coast of Florida*. Report prepared for Shell Oil Company. Houston: Florida Audubon Society.
King, B. 1973. Bonaparte's Gull in Cornwall "foot paddling" to disturb organisms. *Br. Birds* 66:447.
King, J. G., and G. A. Sanger. 1979. Oil vulnerability index for marine oriented birds. In *Conservation of marine birds of northern North America, wildlife research report 11*, ed. J. C. Bartonek and D. N. Nettleship, 227-239. Washington, DC: U.S. Department of the Interior.
Kittleson, B. C. 1976. Third record of the Arctic Loon from Florida. *Fla. Field Natur.* 4(1):17.
Krebs, J. R. 1974. Colonial nesting and social feeding as strategies for exploiting food resources in the Great Blue Heron (*Ardea herodias*). *Behavior* 51(1-2): 99-134.
Kushlan, J. A. 1973. Least Bittern nesting colonially. *Auk* 90:685-686.
Kushlan, J. A. 1974. The ecology of the White Ibis in southern Florida, a regional study. Ph.D. diss., Univ. of Miami.
Kushlan, J. A. 1978a. Feeding ecology of wading birds. In *Wading birds*, ed. A. Sprunt IV, J. C. Ogden, and S. Winckler, 249-297. New York: National Audubon Society.
Kushlan, J. A. 1978b. White Pelican numbers in Everglades National Park. *Fla. Field Natur.* 6:16-17.
Kushlan, J. A. 1982. The Sandhill Crane in the Everglades. *Fla. Field Natur.* 10:74-76.
Kushlan, J. A., and O. L. Bass, Jr. 1983a. Decreases in the southern Florida Osprey population, a possible result of food stress. In *Biology and management of Bald Eagles and Ospreys*, ed. D. M. Bird, 187-200. Harpell Press.
Kushlan, J. A., and O. L. Bass, Jr. 1983b. Habitat use and the distribution of the Cape Sable Sparrow. In *The Seaside Sparrow, its biology and management*, 139-146. N. C. Biol. Survey and N. C. State Museum.
Kushlan, J. A., and E. J. Fisk. 1972. Range expansion of the Killdeer in Florida. *Bird Banding* 43:261-263.
Kushlan, J. A., and P. C. Frohring. 1983. Foraging relationships of wading birds in the Everglades Estuary. *Bird Behavior* 1:1-51.
Kushlan, J. A., and P. C. Frohring. 1985. Decrease in Brown Pelican populations in south Florida. *Colonial Waterbirds* 8:83-95.
Kushlan, J. A., and P. C. Frohring. 1986. The history of the southern Florida Wood Stork population. *Wilson Bull.* 98:368-386.
Kushlan, J. A., and D. A. White. 1975. *A survey of nesting wading birds in southern Florida 1974-1975*. Resource Management Report, Everglades National Park. Homestead, FL.
Kushlan, J. A., and D. A. White. 1977a. Nesting wading bird populations in southern Florida. *Fla. Sci.* 40:65-72.
Kushlan, J. A., and D. A. White. 1977b. Laughing Gull colonies in extreme southern Florida. *Fla. Field Natur.* 5:44-46.
Kushlan, J. A., O. L. Bass, Jr., and L. C. McEwan. 1982. Wintering waterfowl in the Everglades estuaries. *Am. Birds* 36:815-819.
Layne, J. N. 1981. Nesting development of the young, and parental behavior in a pair of Florida Sandhill Cranes. *Fla. Field Natur.* 9:51.
Lincoln, F. C. 1939. *The migration of American birds*. New York: Doubleday, Doran and Co., Inc.
Loflin, R. K. 1983. Communal behaviors of the Smooth-billed Ani (*Crotophaga ani*). Ph.D. diss., Univ. of Miami.
Lowery, G. H., Jr. 1974. *Louisiana Birds, 3rd Ed.* Baton Rouge: Louisiana State Univ.
McEwan, L. C., and J. A. Kushlan. 1977. *Status of colonial birds, April-June 1977*. Report prepared for the Everglades National Park. Homestead, FL.
McIntyre, H. 1986. The Common Loon. In *Audubon wildlife report 1986*, ed. R. C. O. Silvestro, 678-695. New York: National Audubon Society.
Mills, G. S. 1976. American Kestrel sex ratios and habitat separation. *Auk* 93:740-748.

Morrison, R. I. G. 1984. Migration systems of some New World shorebirds. In: *Shorebirds, migration and foraging behavior, behavior of marine animals, Vol. 6*, ed. J. Burger and B. L. Olla, 125-202. New York: Plenum Press.
Myers, J. P. 1988. The Sanderling. In *Audubon wildlife report 1988-1989*, ed. W. J. Chandler, 651-666. New York: Academic Press, Inc.
Nesbitt, S. A., J. C. Ogden, H. W. Kale II, B. Patty, and L.A. Rowse. 1982. *Florida atlas of breeding sites for herons and their allies: 1976-1978*. U.S. Department of the Interior, U.S. Fish and Wildlife Service.
Nisbet, I. C. T. 1989. The Roseate Tern. In *Audubon wildlife report 1989/1990*, ed. W. J. Chandler, 479-497. San Diego: Academic Press.
Oberholser, H. C. 1974. *The bird life of Texas. Vol. 1*. Austin: Univ. of Texas Press.
Ogden, J. C. 1974a. The Short-tailed Hawk in Florida. I. Migration, habitat, hunting techniques and food habits. *Auk* 91:95-110.
Ogden, J. C. 1974b. Aspects of the Red-shouldered Hawk nesting in southern Florida. *Fla. Field Natur.* 2:25-27.
Ogden, J. C. 1978a. Wood Stork. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 3-4. Gainesville: Univ. Presses of Fla.
Ogden, J. C. 1978b. Osprey. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 30-32. Gainesville: Univ. Presses of Fla.
Ogden, J. C. 1978c. Roseate Spoonbill. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 52-54. Gainesville: Univ. Presses of Fla.
Ogden, J. C. 1978d. Short-tailed Hawk. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 55-57. Gainesville: Univ. Presses of Fla.
Ogden, J. C. 1978e. Snowy Egret. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 75-76. Gainesville: Univ. Presses of Fla.
Ogden, J. C. 1978f. Louisiana Heron. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 77-78. Gainesville: Univ. Presses of Fla.
Ogden, J. C. 1985. The Wood Stork. In *Audubon wildlife report 1985*, ed. R. L. Di Silvestro, 458-470. New York: National Audubon Society.
Owre, O. T. 1967. Adaptations for locomotion and feeding in the Anhinga and the Double-crested Cormorant. *Am. Ornithol. Union Monogr.* 6:138.
Owre, O. T. 1978a. White-crowned Pigeon. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 43-45. Gainesville: Univ. Presses of Fla.
Owre, O. T. 1978b. Black-whiskered Vireo. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 59-61. Gainesville: Univ. Presses of Fla.
Owre, O. T. 1978c. Burrowing Owl. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 97-99. Gainesville: Univ. Presses of Fla.
Owre, O.T. 1978d. Mangrove Clapper Rail. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 113-114. Gainsville: Univ. Presses of Fla.
Page, G., and D. F. Whitacre. 1975. Raptor predation on wintering shorebirds. *Condor* 77:73-83.
Palmer, R. S. 1962. *Handbook of North American birds. Vol. 1*. New Haven: Yale Univ. Press.
Palmer, R. S. 1968. Species accounts of shorebirds. In *The shorebirds of North America*, ed. G. D. Stout, 143-267. New York: Viking Press.
Palmer, R. S., ed. 1976a. *Handbook of North American birds. Vol. 2*. New Haven: Yale Univ. Press.
Palmer, R. S., ed. 1976b. *Handbook of North American birds. Vol. 3*. New Haven: Yale Univ. Press.
Portnoy, J. W., R. M. Erwin, and T. W. Custer. 1981. *Atlas of gull and tern colonies: North Carolina to Key West, Florida (including pelicans, cormorants and skimmers)*. FWS/OBS-80-05. Washington, DC: U.S. Fish and Wildlife Service, Office of Biological Services.
Powell, G. V. N. 1983. Food availability and reproduction of Great White Herons, *Ardea herodias*: a food addition study. *Colonial Waterbirds* 6:139-147.
Powell, G. V. N. 1987. Habitat used by wading birds in a subtropical estuary: implications of hydrography. *Auk* 104:740-749.
Powell, G. V. N., R. D. Bjork, J. C. Ogden, R. T. Paul, A. H. Powell, and W. B. Robertson, Jr. 1989. Population trends in some Florida Bay Wading Birds. *Wilson Bull.* 101:436-437.
Ripley, S. D. 1977. *Rails of the world*. Boston: David R. Godine.
Roberts, T. S. 1932. *Birds of Minnesota. Vol. 1*. Minneapolis: Univ. Minnesota Press.
Robertson, W. B., Jr. 1964. The terns of the Dry Tortugas. *Bull. Fla. State Mus. Biol. Sci.* 8(1):1-94.
Robertson, W. B., Jr. 1971. The changing seasons; the fall migration: August 15 - November 30, 1970. Florida region. *Am. Birds* 25:44-49.
Robertson, W. B., Jr. 1978a. Rothschild's Magnificent Frigate-bird. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 25-27. Gainesville: Univ. Presses of Fla.
Robertson, W. B., Jr. 1978b. Florida Great White Heron. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 69-72. Gainesville: Univ. Presses of Fla.
Robertson, W. B., Jr. 1978c. Southern Bald Eagle. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 27-30. Gainesville: Univ. Presses of Fla.
Robertson, W. B., Jr. 1978d. Roseate Tern. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 39-40. Gainesville: Univ. Presses of Fla.
Robertson, W. B., Jr. 1978e. Reddish Egret. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 51-52. Gainesville: Univ. Presses of Fla.
Robertson, W. B., Jr. 1978f. Mangrove Cuckoo. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 57-58. Gainesville: Univ. Presses of Fla.
Robertson, W. B., Jr. 1978g. Common (or Antillean) Nighthawk. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 58-59. Gainesville: Univ. Presses of Fla.
Robertson, W. B., Jr. 1978h. Cuban Yellow Warbler. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 61-62. Gainesville: Univ. Presses of Fla.
Robertson, W. B., Jr., and C. R. Mason. 1965. Additional bird records from the Dry Tortugas. *Fla. Natur.* 38:131-138.
Rodgers, J. A., Jr. 1978. Little Blue Heron. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 72-73. Gainesville: Univ. Presses of Fla.
Rodgers, J. A., Jr. 1982. Food of nestling Little Blue Herons on the west coast of Florida. *Fla. Field Natur.* 10(2):25-44
Rodgers, J. A., Jr. 1983. Foraging behavior of seven species of herons in Tampa Bay, Florida. *Colonial Waterbirds* 6:11-23.

Root, T. 1988. *Atlas of wintering North American birds. An analysis of the Christmas bird count data*. Chicago: Univ. Chicago Press.
Schorger, A. W. 1947. The deep diving of the loon and Old-squaw and its mechanism. *Wilson Bull.* 59:151-159.
Schreiber, R. W. 1976. Movements of color marked Brown Pelicans. *Bird Banding* 47:101-111.
Schreiber, R. W. 1978a. Eastern Brown Pelican. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 23-25. Gainesville: Univ. Presses of Fla.
Schreiber, R. W. 1978b. Caspian Tern. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 94. Gainesville: Univ. Presses of Fla.
Schreiber, R. W., and W. B. Robertson, Jr. 1975. Nesting of the Brown Pelican (*Pelecanus occidentalis*) on the Dry Tortugas, Florida. *Fla. Field Natur.* 3:47-48.
Sidle, J. C., W. H. Koonz, and K. Roney. 1985. Status of the American White Pelican: An update. *Am. Birds* 39:859-864.
Snyder, H. 1978. Peregrine Falcon. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 7-8. Gainesville: Univ. Presses of Fla.
Spendelow, J. A., and S. R. Patton. 1988. *National atlas of coastal waterbird colonies in the contiguous United States: 1976-1982*. U.S. Fish Wildl. Serv. Biol. Rep. No 88(5).
Sprunt, A., Jr. 1954. *Florida bird life*. New York: Coward-McCann, Inc.
Sprunt, A., Jr. 1962. Birds of the Dry Tortugas. *Fla. Natur.* 35(2):34-48,58.
Sprunt, A., Jr. 1963. *Addendum to Florida bird life*. Privately printed.
Stevenson, H. M. 1978. Florida Prairie Warbler. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 105-106. Gainesville: Univ. Presses of Fla.
Stieglitz, W. O. 1972. Food habitats of the Florida duck. *J. Wildl. Manage.* 32:921-938.
Stieglitz, W. O., and C. J. Wilson. 1968. Breeding biology of the Florida duck. *J. Wildl. Manage.* 36:422-428.
Stresemann, E., and D. Amadon. 1979. Order Falconiformes. In *Checklist of birds of the world. Vol. 1*, ed. E. Mayr and G. W. Cottrell, 271-425. Cambridge: Museum of Comparative Zoology.
Sykes, P. W., Jr. 1978. Black Rail. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 114-115. Gainesville: Univ. Presses of Fla.
Terres, J. K. 1980. *The Audubon Society encyclopedia of North American birds*. New York: Alfred A. Knopf.
Walkinshaw, L. H. 1949. The Sandhill Crane. *Cranbrook Inst. Sci. Bull.* 29:202.
Wallace, G. J., and H. D. Mahan. 1975. *An introduction to ornithology, 3rd Ed.* New York: MacMillan Publ. Co., Inc.
Wamer, N. O. 1980. Sight records of the Arctic Tern on the Gulf Coast of Florida. *Fla. Field Natur.* 8:49.
Werner, H. W. 1978. Cape Sable Seaside Sparrow. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 19-20. Gainesville: Univ. Presses of Fla.
Westall, M. A. 1986. Osprey. In *Audubon wildlife report 1986*, ed. R. L. Di Silvestro, 888-909. New York: National Audubon Society.
Wiese, J. H. 1978. Great Egret. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 73-75. Gainesville: Univ. Presses of Fla.
Wiley, J. W. 1978a. Southeastern American Kestrel. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 32-34. Gainesville: Univ. Presses of Fla.
Wiley, J. W. 1978b. Merlin. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 111-112. Gainesville: Univ. Presses of Fla.
Wiley, J. W., and B. N. Wiley. 1979. The biology of the White-crowned Pigeon. *Wildl. Monogr.* 64:1-54.
Wolf, L. L., and F. B. Gill. 1961. Flock feeding behavior in migrant Bonaparte's Gulls. *Wilson Bull.* 73:389-390.
Woolfenden, G. E. 1967. Selection for a delayed simultaneous wing molt in loons (Gaviidae). *Wilson Bull.* 79:416-419.
Woolfenden, G. E. 1978a. Snowy Plover. In *Rare and endangered biota in Florida. Vol. 2, Birds*, ed. H. W. Kale II, 8-10. Gainesville: Univ. Presses of Fla.
Woolfenden, G. E. 1978b. Piping Plover. In *Rare and endangered biota of Florida. Vol. 2, Birds*, ed. H. W. Kale II, 88. Gainesville: Univ. Presses of Fla.
Woolfenden, G. E., and R. W. Schreiber. 1973. Common birds of the saline habitats of the eastern Gulf of Mexico: their distribution, seasonal status, and feeding ecology. In *A summary of knowledge of the eastern Gulf of Mexico, 1973*, 11-22. St. Petersburg: State Univ. System of Florida, Institute of Oceanography.