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Integrated Conceptual Ecosystem Model Development for the Southeast Florida Coastal Marine Ecosystem

MARine Estuarine goal Setting (MARES) for South Florida

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Preface

In a very real sense, the MARine and Estuarine goal Setting (MARES) project is an ambitious sociological experiment. Its overall goal is to "reach a science-based consensus about the defining characteristics and fundamental regulating processes of a South Florida coastal marine ecosystem that is both sustainable and capable of providing diverse ecosystem services." The approach taken in pursuing this goal is based on the hypothesis that scientists participating in a systematic process of reaching consensus can more directly and effectively contribute to critical decisions being made by policy makers and by natural resource and environmental management agencies. This report is an intermediate product of this consensus-building process.

South Florida is the site of the world's largest and most expensive ecosystem restoration effort: the Comprehensive Everglades Restoration Plan (CERP). While a great many natural system scientists have participated in CERP, it is difficult or impossible to determine whether their contributions have made any difference. Human dimension scientists (economists, sociologists, cultural anthropologists, etc.) have been given only limited opportunity to participate. Moreover, CERP has focused upon the South Florida peninsula itself, not upon the surrounding coastal marine ecosystem. This is despite significant, well documented, deleterious environmental changes occurring in the surrounding coastal ecosystem.

The MARES project is an attempt to make science more relevant to the ecosystem restoration effort in South Florida and to facilitate ecosystem-based management (EBM) in the region's coastal marine ecosystem. The project is funded by the Center for Sponsored Coastal Ocean Research, a program of NOAA's National Ocean Service.

The first step in the MARES process is to convene experts (both natural system and human dimension scientists), stakeholders, and agency representatives for the three subregions of the South Florida coastal marine ecosystem. Each group of experts is charged with drawing their shared understanding of the fundamental characteristics and processes that regulate and shape the ecosystem into a conceptual diagram (MARES infographic).

The second step is to build upon these diagrams to articulate conceptual ecosystem models that reference the existing scientific knowledge. Development of the conceptual models employs a framework (DPSER: Drivers/Pressures/State/Ecosystem Services/Responses) that explicitly incorporates information about the effects that people have upon and the benefits they gain from the ecosystem. We refer to the conceptual models developed with this approach as Integrated Conceptual Ecosystem Models (ICEMs) because people are treated as an integral part of the ecosystem, in contrast to the conceptual models developed previously for CERP.

The third step in the MARES process is to identify subregional indicators that characterize conditions in the ecosystem, both societal and ecological, and the gaps in our existing knowledge. Identification of these indicators builds on the consensus understanding contained in the ICEMs, which synthesize existing information on the ecosystem.

The indicators being developed by the MARES project are combined into a set of regional indices that can be incorporated into coastal ecosystem score cards. Implementing a score card process, such as has been done for the freshwater wetlands in CERP based upon such a set of indices, would rigorously document trajectories towards (or away from) a sustainable and satisfactory condition. Where specific seemingly critical indices cannot be calculated due to a lack of data, the information gaps identified thereby can be used by science agencies (e.g., NOAA, the National Science Foundation, or U.S. Geological Survey) to prioritize their external and internal allocation of research resources. The ICEMs and indicators organize scientific information about the relationship between people and the environment and the trade-offs that managers face in their decisions.

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Acronyms

DPSER	Drivers-Pressures-State-Ecosystem Services-Response
EBM	Ecosystem-based Management
EI	Ecosystem Index
FK/DT	Florida Keys/Dry Tortugas
ICEM	Integrated Conceptual Ecosystem Model
MARES	MARine and Estuarine goal Setting project
QEI	Quantitative Ecosystem Indicator
SEFC	Southeast Florida Coast
SFCME	South Florida coastal marine ecosystem
SWFS	Southwest Florida Shelf

Abstract

The overall goal of the MARES (MARine and Estuarine goal Setting) project for South Florida is "to reach a science-based consensus about the defining characteristics and fundamental regulating processes of a South Florida coastal marine ecosystem that is both sustainable and capable of providing the diverse ecosystem services upon which our society depends." Through participation in a systematic process of reaching such a consensus, science can contribute more directly and effectively to the critical decisions being made both by policy makers and by natural resource and environmental management agencies. The document that follows briefly describes MARES overall and this systematic process. It then describes in considerable detail the resulting output from the first step in the process, the development of an Integrated Conceptual Ecosystem Model (ICEM) for the third subregion to be addressed by MARES, the Southeast Florida Coast (SEFC). What follows with regard to the SEFC relies upon the input received from more than 60 scientists, agency resource managers, and representatives of environmental organizations during workshops held throughout 2009–2012 in South Florida.

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Introduction

The South Florida coastal marine ecosystem (SFCME) comprises the estuaries and coastal waters extending from Charlotte Harbor and the Caloosahatchee Estuary on the west coast, through the Florida Keys, and up the east coast to St. Lucie Inlet. For many who live in the region or visit here, the SFCME defines South Florida. The SFCME is a valuable natural resource that supports a significant portion of the South Florida economy through the goods and services provided by the ecosystem.

The MARine and Estuarine goal Setting (MARES) project develops three types of information that will be useful for managers and stakeholders working to sustain the SFCME and the goods and services it provides. First, conceptual diagrams draw together, in graphical form, the fundamental characteristics and processes that shape and regulate the ecosystem. Second, Integrated Conceptual Ecosystem Models (ICEMs) describe in detail the key ecosystem components and processes and how these are affected by human activities. Third, Quantitative Ecosystem Indicators (QEIs) inform managers and stakeholders on the condition of the SFCME relative to those conditions needed to sustain the ecosystem.

This, the third report of the MARES project, documents the development of a conceptual ecosystem model for the coastal marine waters surrounding the Southeast Florida Coast (SEFC). The report begins with an overview of the SFCME and an introduction to the key concepts and terminology of the framework used to guide development of the conceptual models, the MARES Drivers-Pressures-State-Ecosystem Services-Response (DPSER) model. Companion reports document the conceptual models developed to describe the other regions within the SFCME.

Three Distinct Subregions within the South Florida Coastal Marine Ecosystem

South Florida coastal waters extend around the southern tip of the Florida peninsula from Charlotte Harbor on the west coast to the St. Lucie Inlet on the east coast and contain three distinct, but highly connected coastal regions (Figure 1). The oceanography of these regions varies considerably due to geomorphology and to local and regional oceanographic processes. From west to east, the three coastal subregions are the Southwest Florida Shelf (SWFS), the Florida Keys/Dry Tortugas (FK/DT), and the SEFC. The SFCME also includes two large estuarine embayments—Florida Bay and Biscayne Bay—and several smaller estuarine systems, such as the Caloosahatchee Estuary.

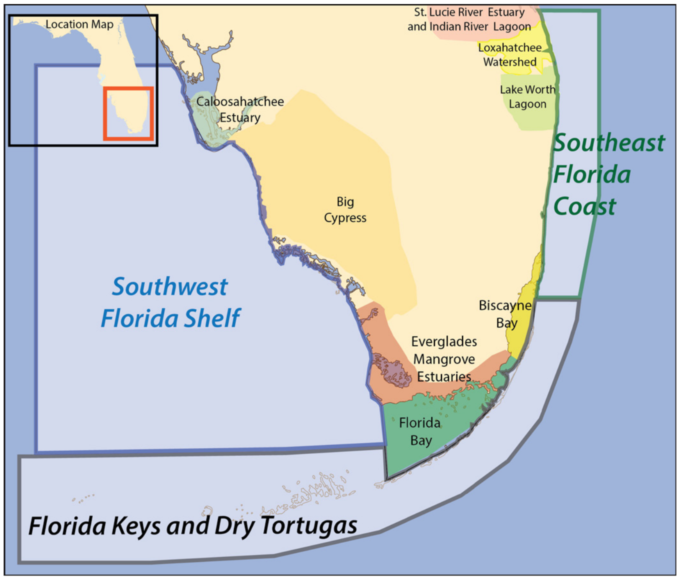


Figure 1. Map of the South Florida coastal marine ecosystem and three MARES subregions.

Each subregion exhibits distinct geomorphic and oceanographic characteristics. The SWFS encompasses the broad, shallow shelf from the Caloosahatchee Estuary to the Florida Keys and Dry Tortugas region. Oceanographic conditions here, characterized by long residence time (waters remain in a general location for a period of time) and susceptibility to stratification (waters become arranged in a layered configuration, e.g., hot at the top, cool at the bottom), favor the development of phytoplankton blooms. The FK/DT subregion encompasses the shallow, subtropical waters surrounding the Florida Keys and sits between the SWFS and Gulf of Mexico to the north and the energetic Florida Current system offshore to the south. The SEFC subregion is characterized by a relatively narrow shelf formed by the northern extent of the Florida Reef Tract. Eddies carried along the seaward edge of the SEFC subregion by the Florida Current influence conditions over the reef, driving the exchange with surface waters of the Florida Current and with waters upwelled from deeper depths along the shelf edge.

Currently, coastal management programs are administered on scales that are, in general, smaller than these subregions, rather than at the scale of the total SFCME. Issues of interest for ecosystem management are defined both at the scale of the SFCME in its entirety, essentially surrounding and overlapping with the geographic scope of the South Florida Ecosystem Restoration Task Force, and at smaller legal or jurisdictional boundaries (cities and counties). To support these diverse interests, descriptions of the coastal marine ecosystem occur first at the subregional scale, which recognizes the distinctive character of the ecosystem along the SWFS, surrounding the Florida Keys, and along the SEFC. It is recognized that the MARES DPSER model must encompass a variety of spatial scales to capture the total SFCME.

The MARES project uses the terms "local," "regional," and "global" to distinguish different spatial scales at which drivers and pressures act on the ecosystem, as well as the scope of management actions. With respect to management, the local scale corresponds to the smallest scale at which management occurs, i.e., at the county level: Monroe, Miami-Dade, Broward, Palm Beach, Martin, Collier, and Lee. The regional scale corresponds to the area that contains the entire SFCME, while the global scale refers to factors arising from causes outside South Florida.

Oceanographic Processes Connect Subregions

South Florida coastal areas benefit from a regional-scale recirculation pattern formed by the interplay of currents that connect the MARES subregions (Figure 2). The recirculation system has significant influence on maintaining the health, diversity, and abundance of South Florida's valuable coastal

Adapted from Kruczynski and Fletcher (2012).

Figure 2. Oceanographic processes in the South Florida coastal marine ecosystem.

marine ecosystems, including seagrass, fish and shellfish, and benthic habitats. The overall pattern of water flow is south along the west Florida coast in the Gulf of Mexico, east through the Florida Straits, and then north along the Southeast Florida Shelf. The recirculation is provided by the combination and merger of four distinct current systems: (1) downstream flow of the Loop Current and Florida Current offshore of the SWFS and Florida Keys; (2) returning countercurrent flows in the Lower Keys and Dry Tortugas from prevailing westward winds; (3) enhancement of the countercurrent in the Florida Keys from passage of Florida Current cyclonic frontal eddies, which also act to retain particles within interior eddy recirculations; and (4) net southward flow through the SWFS that can return waters to the Florida Keys Atlantic Coastal Zone following northward excursions onto the SWFS from transient wind or eddy-driven transports.

Eddies are particularly important to the health and well-being of the marine life and coastal waters of Florida due to the state's location, peninsular shape, and the movement of the Gulf Stream. Ocean eddies are rotating bodies of water that form along the boundaries of major ocean currents. They come in different sizes, shapes, and rotation directions, ranging from large separations of the parent oceanic flows that form into warm or cold core rings several hundred kilometers across to small-scale turbulent vortices that mix fluids across the current boundary.

A continuous stream of eddies move downstream, northward, along the shoreward boundary of the Gulf Stream from the Gulf of Mexico, through the Straits of Florida, and along the southeast U.S. coast up to Cape Hatteras (Lee *et al*., 1991). These eddies are visible from space as cold, cyclonic rotating water masses interacting with the coastal waters of Florida and the states in the southeastern portion of the U.S. The eddies develop from growing disturbances of the Gulf Stream frontal boundary and are hence termed "frontal eddies."

The cold interior water of the eddies stems from upwelling of deeper, nutrient-rich strata of the Gulf Stream, which provides a basic food supply to support ecosystem development within the eddies and adjacent coastal environments. Circulation within the eddies provides a retention mechanism for newly-spawned larvae which, combined with the available food supply, enhances the survival and condition of new recruits to the Florida Keys coastal waters and reef communities. For example, larvae spawned in the Dry Tortugas can be spread all along the Florida Keys by the movement and evolution of frontal eddies. The passage of frontal eddies also acts to increase the exchange of coastal waters with offshore waters of the Florida Current and, thereby, helps to maintain the natural water quality of the coastal ecosystem (Lee *et al.,* 2002; Sponaugle *et al.,* 2005; Hitchcock *et al.,* 2005).

The SWFS is the southern domain of the wide, shallow West Florida Shelf. It receives moderate freshwater from small rivers and estuaries and undergoes seasonal stratification in the spring and summer (Weisberg *et al.,* 1996). Currents over the mid to inner shelf are due primarily to wind and tidal forcing that align with the shelf's smooth north-south oriented topography (Mitchum and Sturges, 1982). Outer shelf flows are controlled by the Loop Current and eddies that move downstream along its shoreward boundary and vary considerably on day-to-month time scales. Warm eddies can separate from the Loop Current and move along the Dry Tortugas and Florida Keys Reef Tract. These separations cause instabilities that result in cold (upwelling), cyclonic frontal eddies that can be carried around the Loop Current and into the Straits of Florida and strongly interact with outer shelf waters (Paluszkiewicz *et al.,* 1983; Fratantoni *et al.,* 1998; Hamilton and Lee, 2005; Lee *et al.,* 2002).

Loop Current penetrations into the eastern Gulf of Mexico extend northward, sometimes reaching to the outer shelf off the Mississippi River delta and entraining river water for transport to the Florida Keys (Ortner *et al.*, 1995). Eventually, an extended Loop Current becomes unstable and separates into a large (200-300 km), clockwise rotating warm eddy that leaves a young Loop Current to the south where it turns directly into the Straits of Florida and parallels the Florida Keys. Mean flows over the SWFS appear to be related to the Loop Current and are toward the south, connecting the southwest shelf to the Florida Keys Reef Tract through the passages in the keys island chain.

The FK/DT coastal region has a narrow shelf with a complex shallow reef topography that parallels the north-south (Upper Keys) to east-west (Middle and Lower Keys) curving chain of islands. Coastal waters tend to remain well mixed throughout the year, and there are no significant freshwater sources. Mid- to inner-shelf currents are primarily toward the west in the Lower Keys, due to prevailing westward (downwelling) winds, and shift to northward currents in the Upper Keys due to winds from the southeast that have a northward component and the close proximity of the northward flowing Florida Current (Lee and Williams, 1999; Lee *et al.,* 2002).

Waters of the SEFC are highly connected to the upstream regions of the FK/DT and SWFS by the strong northward flow along the edge of the Florida Current. The SEFC region consists of a narrow coastal zone stretching north-south 176 km from Biscayne Bay to the St. Lucie Inlet. The portion of the shelf between Miami and Palm Beach counties is unusual in that it is extremely narrow and shallow, varying in width from 1-3 km, with only 30 m water depth at the shelf break. Coastal waters here are bounded by the highly developed shoreline of southeast Florida and the strong northward flowing Florida Current at the shelf break.

The interaction of coastal and inshore waters takes place through nine tidal inlets, plus the wide and shallow “safety valve” opening to Biscayne Bay. Ocean currents play a major role in the transport and exchange of physical, chemical, and biological properties both along and across the shelf. Changes in the water column in the mid- to outer-shelf region are a direct result of the proximity to the powerful, northward flowing Florida Current with its continually evolving stream of onshore/offshore frontal meanders and small (10-30 km), cyclonic, cold-core eddies (Lee, 1975; Lee and Mayer, 1977). Upwelling in the eddy cores causes uplifting of the nutrient supply in the upper mixed layer of the ocean (nutricline) along the continental slope that can penetrate the upper layers of the water column (euphotic zone) and stimulate primary production (Lee *et al*., 1991).

The proximity of the Florida Current to the shelf break results in strong northward mean flows over the outer shelf ranging from 25-50 cm/sec. Currents near the coast are primarily in the alongshore direction (south-north) and controlled by tides and winds. Mean flows are weak and follow seasonally-averaged winds. Downstream movement of eddies along the outer shelf results in strong interactions between the Florida Current and adjacent shelf waters. Flow and temperature variability within the mid- to outer-shelf regions are dominated by the northward passage of these frontal eddies, which occur at an average frequency of once per week throughout the year with little seasonal change. Eddy passages normally take one to two days and result in considerable exchange between resident shelf waters that remain on the shelf for a period of time and new Florida Current waters within the eddy. Displacement of shelf waters by eddies at an average weekly interval represents a flushing mechanism and a mean residence time of shelf waters of approximately one week. Nearshore waters lack any significant river discharge and tend to be well mixed throughout the year.

Building a Foundation for Ecosystem-Based Management

Ecosystem-based management (EBM) is an adaptive, holistic approach to dealing with the complexity of environmental challenges. Since 2010, implementing EBM has become a guiding directive in the federal management of U.S. coastal resources (Lubchenco and Sutley, 2010). Forging a vision of the ecosystem shared by all, managers and stakeholders, is an essential initial step. The overall goal of the MARES project, to reach a science-based consensus about the defining characteristics and fundamental regulating processes of a sustainable SFCME, addresses this need directly.

The MARES project builds on previous efforts to implement EBM in connection with the hydrological restoration of the Everglades, the vast freshwater wetlands that occupy the central portion of the South Florida peninsula. Work on the Comprehensive Everglades Restoration Plan (CERP) was authorized in 2000, but planning and preparation began in the 1990s. Ogden *et al.* (2005) developed a set of conceptual ecological models for the ecosystems in the region that are directly affected by CERP. The CERP models have proven instrumental in (1) selection of performance measures and indicators, (2) implementation of regional monitoring plans, and (3) identification of critical research gaps. However, coverage by CERP conceptual models did not include the regional coastal marine ecosystem (i.e., Florida Bay, Biscayne Bay), nor did they specifically include human society and its complex relationship with the environment.

The conceptual models developed by the MARES project extend these efforts geographically, by moving offshore into the coastal marine ecosystem, and conceptually, by explicitly including human society as an integral component of the ecosystem. From an EBM perspective, it is essential to consider social, cultural, and economic factors, in both the research and management context, along with ecological variables (Weinstein, 2009; Cheong, 2008; Turner, 2000; Lubchenco, 1999; Visser, 1999). Few people live in the remaining natural area of the Everglades, and the conceptual models developed for CERP do not explicitly include human activities, such as hunting, fishing, sightseeing, etc., as part of the ecosystem, except as drivers of change in the natural ecosystem. By contrast, most of the 6.5 million people residing in South Florida live near the coast, and many residents and visitors receive benefits from the SFCME resources and services.

The first step in the MARES process is to convene the relevant scientific experts (both natural system and human dimensions), stakeholders, and agency representatives within each subregion and charge them with developing a visual representation of their shared understanding of the fundamental characteristics and processes regulating and shaping the ecosystem. The approach being taken in the MARES project encourages scientists to participate in a systematic, inclusive process of reaching consensus. The process of consensus building avoids the adversarial approach that often hinders the application of scientific information. Through consensus building, scientists can contribute more directly and effectively to the critical decisions being made by policy makers and by natural resource and environmental management agencies (Karl *et al.,* 2007).

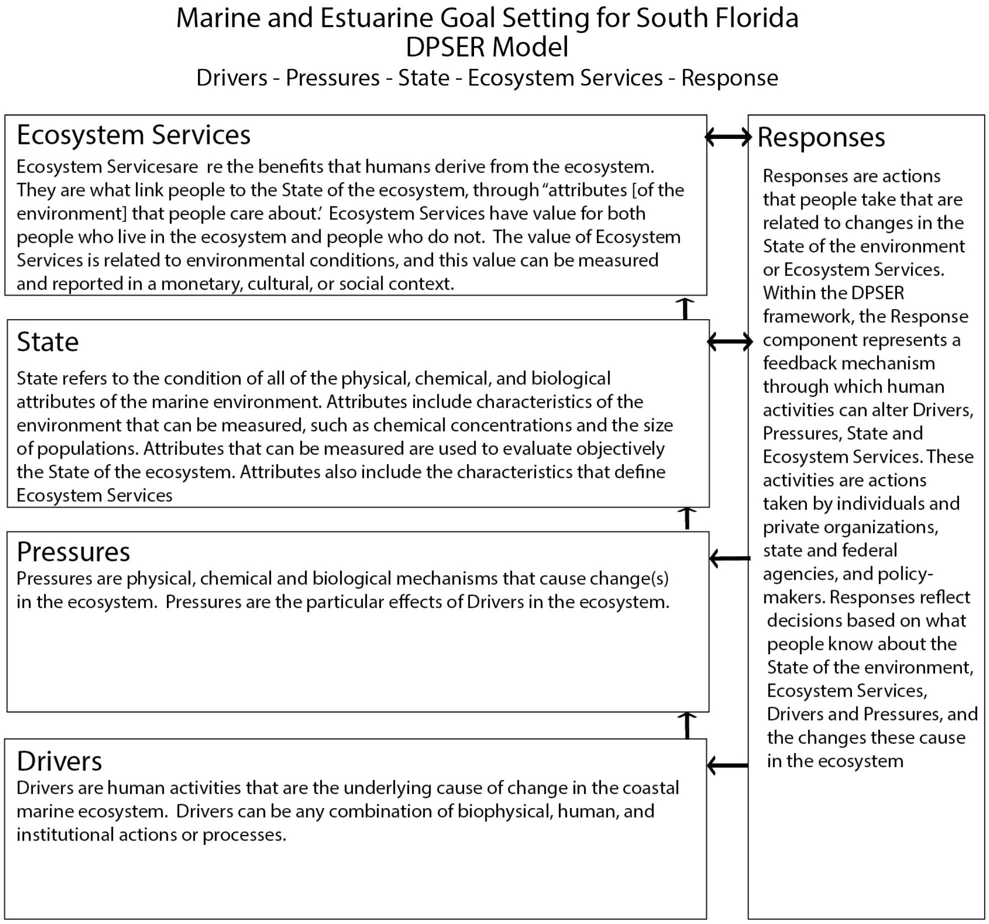
The second step is to build upon these diagrams to develop ICEMs. This process is then repeated for each of the three subregions. The ICEMs serve as the basis for synthesizing our scientific knowledge. They also help complete the third and final step to identify subregional indicators, QEIs (both societal and ecological), as well as major knowledge or information gaps. The QEIs are combined into a parsimonious or smaller set of ecosystem indexes (EIs) that can be incorporated into a total system score card of overall coastal ecosystem status. A total system score card can provide information as to the trajectory of the SFCME towards (or away) from a sustainable and satisfactory condition. Individual EIs (or smaller sets of indicators and metrics) may be used by different agencies with specific mandates or responsibilities to make explicit the benefits of (but also the tradeoffs between) alternative management options.

The MARES Model Framework

MARES relies upon a specific conceptual framework derived from the economic *Driver-Pressures-State-Impacts-Responses* (DPSIR) model (Tscherning *et al.,* 2012; OECD, 1993). While DPSIR has been used to inform environmental management (Mangi *et al.,* 2007), it does not explicitly incorporate the benefits that humans derive from the ecosystem. Moreover, *Impacts* imply that the effect of human society upon *State* is primarily negative and that *Responses* are warranted only after these impacts occur. MARES concludes this is insufficient for capturing the complex human dimensions of the integrated ecosystem. Efforts have been made to integrate *Ecosystem Services* and societal benefits into DPSIR models but in a somewhat indirect manner (Atkins *et al.,* 2011). In the MARES DPSER model, human benefits from the environment are represented in the *Ecosystem Services* element (Figure 3).

Humans are integrated into every element of the DPSER framework, including the effects that people have on the environment and the values that motivate their actions to sustain the regional ecosystem. The first two elements of the model framework, *Drivers* and *Pressures*, describe factors that cause change in the condition of the SEFC marine environment. *State* describes the coastal marine environment in terms of attributes that relate to *Ecosystem Services*. The *Response* element of the DPSER model framework describes decisions and actions people take to sustain or increase the *Ecosystem Services* they value. Therefore, the *Response* element introduces the notion of feedback and control into the DPSER model's representation of the integrated ecosystem and embodies the concept of EBM.

The DPSER model provides a framework for organizing social science and natural science information in a format that brings to light the relationship between humans and the environment. The managers can use information assembled by the DPSER model to set priorities and to support management decisions by examining tradeoffs among the relationships between people and the environment. Identifying the "attributes that people care about" addresses the questions of "Who cares?" and "What do they gain or lose from changes in the state of the natural resources and environmental attributes?" "Attributes people care about" are a subset of the attributes used to characterize and define the elements of *Ecosystem Services* and *State*. They serve


Marine and Estuarine Goal Setting for South Florida
DPSER Model
Drivers - Pressures - State - Ecosystem Services - Response

Ecosystem Services
Ecosystem Servicesare re the benefits that humans derive from the ecosystem. They are what link people to the State of the ecosystem, through“attributes [of the environment] that people care about.’ Ecosystem Services have value for both people who live in the ecosystem and people who do not. The value of Ecosystem Services is related to environmental conditions, and this value can be measured and reported in a monetary, cultural, or social context.

State
State refers to the condition of all of the physical, chemical, and biological attributes of the marine environment. Attributes include characteristics of the environment that can be measured, such as chemical concentrations and the size of populations. Attributes that can be measured are used to evaluate objectively the State of the ecosystem. Attributes also include the characteristics that define Ecosystem Services

Pressures
Pressures are physical, chemical and biological mechanisms that cause change(s) in the ecosystem. Pressures are the particular effects of Drivers in the ecosystem.

Drivers
Drivers are human activities that are the underlying cause of change in the coastal marine ecosystem. Drivers can be any combination of biophysical, human, and institutional actions or processes.

Responses
Responses are actions that people take that are related to changes in the State of the environment or Ecosystem Services. Within the DPSER framework, the Response component represents a feedback mechanism through which human activities can alter Drivers, Pressures, State and Ecosystem Services. These activities are actions taken by individuals and private organizations, state and federal agencies, and policy-makers. Responses reflect decisions based on what people know about the State of the environment, Ecosystem Services, Drivers and Pressures, and the changes these cause in the ecosystem

Figure 3. The MARES Drivers-Pressures-State-Ecosystem Services-Response (DPSER) model.

as a link between *Ecosystem Services* and the *State* of the marine environment. *Ecosystem Services* may be evaluated objectively and ranked using techniques developed by resource economists (Farber *et al.,* 2006).

Ecosystem Services are the benefits that people derive from the environment (Farber *et al.,* 2006; Yoskowitz *et al.,* 2010). In assembling information about a marine ecosystem subregion, the MARES project team is asked to consider two questions: “What are the attributes of the coastal marine environment that people care about?” and “Who enjoys the benefits and who suffers the costs when there are changes in ecological attributes?” These questions help avoid the necessity of setting economic benefits to people and benefits to the environment in opposition. People do depend on the *State* of the coastal marine environment and its natural resources for their well-being. People are not only a *Pressure* on the environment; they also act to enhance the environment and the benefits that it provides. Goals may compete, but recognizing the dual roles that people play in the ecosystem should assist managers in balancing competing goals by making tradeoffs explicit.

Ecosystem Services have a value that can be measured by human dimension scientists that MARES measures in both economic and non-economic terms. Knowing the values that people place upon *Ecosystem Services* informs decisions that involve tradeoffs between environmental and other societal objectives and between competing objectives. Assessing the value of *Ecosystem Services* in monetary or economic terms allows a ready comparison with other sources of benefit (Farber *et al.,* 2006). When economic value is difficult to assess or not relevant to the problem, other metrics and approaches are available (Wegner and Pascual, 2011).

Economic values for recreational activities in the Florida Keys were estimated by Leeworthy and Bowker (1997) using a simple model of the economics of natural resource and environmental change. This model shows how actual and perceived changes in environmental attributes and ecosystem services can change the demand for and economic value of outdoor recreation and tourism. Economic values include market and nonmarket values received by users (those participating in recreation activities) and non-users.

Large scale natural resource projects are typically informed by benefit cost analysis in evaluating management alternatives. It is also recognized that there is a suite of values that can influence decision making, e.g., ethical, cultural, and other considerations such as equity, sustainability, and ecological stewardship (Costanza and Folke, 1997). An equity analysis of management alternatives will examine who receives the benefits and who pays the costs, and then make an assessment of whether or not it is fair. Sustainability and stewardship analyses focus on the intertemporal distribution of those services. Cultural and ethical considerations may place constraints on acceptable management decisions (Farber *et al.,* 2006).

State refers to the condition of the coastal marine environment that includes all of the physical, chemical, and biological components of the system. The *State* of the ecosystem is defined, operationally, by attributes. Attributes are a parsimonious subset of all the descriptive characteristics of an environment that represent its overall condition (Ogden *et al.,* 2005). Attributes are measurable and are used to evaluate the ecosystem, e.g., an abundance and diversity of fish found on coral reefs can illustrate the habitat is healthy.

Drivers can be any combination of biophysical, human, and institutional actions or processes. *Drivers* are human activities that are the underlying cause of change in the coastal marine ecosystem and reflect human needs. *Pressures* are the particular manifestations of *Drivers* within the ecosystem. *Pressures* are physical, chemical, and biological mechanisms that directly or proximally cause change in the ecosystem. As such, there is an inherent hierarchical scale between ultimate drivers, which are the expression of human needs and desires to direct *Pressures* on the ecosystem. For example, human population growth leads to increased energy requirements that are met through the burning of fossil fuels. The burning of fossil fuels leads to the emission of carbon dioxide (CO_2) into the atmosphere, which is transferred to the ocean, producing ocean acidification that has a direct *Pressure* on the ecosystem.

Within the DPSER framework, *Response* encompasses human actions motivated either by changes in the condition in the environment (*State*) or in the *Ecosystem Services* provided. Actions that have the effect of altering *Drivers, Pressures,* or *State* of the ecosystem introduce a mechanism for feedback into the system and, therefore, the possibility of control. *Response* includes activities for gathering information, decision making, and program implementation that are conducted by agencies charged with making policies and implementing management actions that affect the SEFC regional ecosystem. Additionally, changes in attitudes and perceptions of the environment by individuals and related changes in behavior that, while less purposeful than the activities of management agencies, can have a large effect on the *Drivers* and *Pressures* acting on the ecosystem are also included.

The Southeast Florida Coastal Marine Region

Physical Setting

Shallow Inshore Waters

The SEFC region comprises the shoreline and the shallow inshore waters, with depths less than 30 m (100 ft), and extends 176 km (110 miles) north from Biscayne Bay to the St. Lucie Inlet (Figure 4). This region is relatively narrow, 3 km (~2 miles) wide off Palm Beach County and 4 km (~2.5 miles) wide off Miami-Dade County. The shelf widens north of Jupiter, where the shoreline becomes more oriented in a northwest-to-southeast direction; the shelf break continues northward and deepens to about 60 m (200 ft). The bottom is composed of three, in some places two, distinct reef tracts that lie parallel to the coastline with interspersed hardbottom and overlying sand deposits. The reef tracts of the SEFC are continuous with the reefs of the Florida Keys to the south that terminate in a submerged beach ridge complex near Jupiter.

Over most of its length the shoreline consists of barrier islands separated from the mainland by narrow, mangrove-lined lagoons (Figure 4). North of Biscayne Bay, the lagoons connect with coastal waters through nine narrow tidal inlets. These inlets are localized sources for the inflow of freshwater

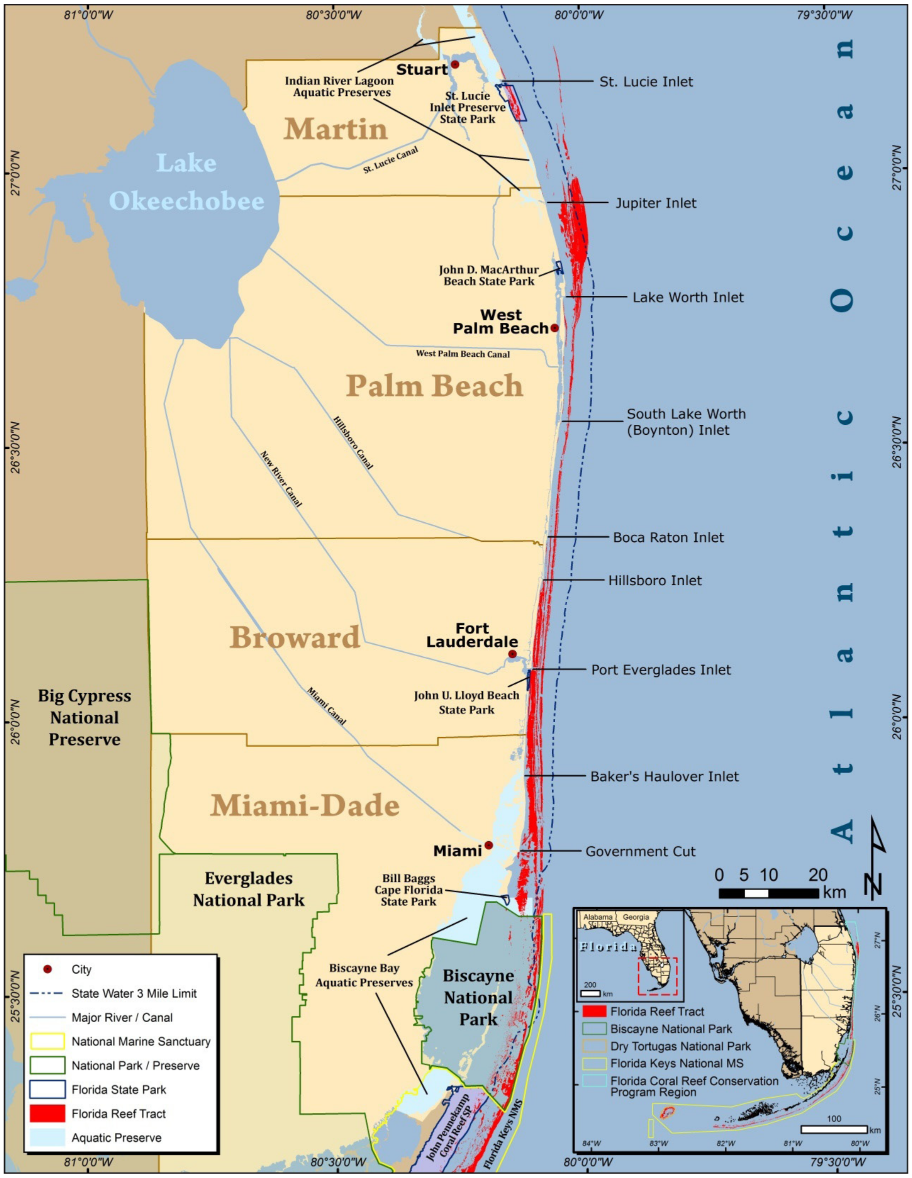


Figure 4. Reef tract along the southeast Florida coastal region.

and nutrients from the mainland. The inlets are also areas of concentrated influence by human activities. Three major seaports are located in Miami, Fort Lauderdale, and Palm Beach. Key Biscayne is the last sandy barrier island in the chain. South of Key Biscayne, the wide, shallow opening of the "Safety Valve" constitutes the seaward boundary of north-central Biscayne Bay, and south of this opening begins the rocky mangrove shoreline that characterizes the Florida Keys to the south.

The narrow shelf along the SEFC does not receive sufficient input of freshwater on a continuous basis to allow buoyancy-driven coastal currents to develop in the inshore region. The inflow of freshwater from the mainland is regulated to prevent upland flooding, and this results in a highly pulsed inflow of freshwater, with high flows occurring in brief periods that coincide with the arrival of tropical storms. South of Palm Beach, ocean disposal of treated wastewater feeds a constant source of freshwater and nutrients in the vicinity of the ocean outfalls, typically 2-5 km (1.5-3 miles) offshore.

Atmospheric forcing controls water temperature, and wind and tides contribute about equally to driving coastal currents (Lee and Mayer, 1977). Tidal currents flow primarily in the alongshore direction, except in areas immediately adjacent to an inlet. Seasonal changes in alongshore winds are primarily responsible for seasonal mean flows. The north-south oriented coastline in the Straits of Florida results in northerly or southerly winds having the greatest influence on currents in these shallow depths. The current response is in the same direction as the wind (north or south) with a lag of less than 6 hours. In the summer, the nearshore mean current is typically toward the north due to the prevailing southeast winds. Prolonged north wind events in the fall result in southward mean flows at the coast. Winter and spring cold front passages cause variable alongshore flows without a preferred mean direction. Magnitudes of seasonally-averaged flows tend to be quite weak in the shallow nearshore region, typically on the order of 1 cm/s.

North of Jupiter Inlet, the shelf widens and opens onto the southern portion of the southeast U.S. continental shelf. Seasonal stratification can develop in the coastal marine waters near St. Lucie, as the result of summer heating and from wind and eddy-induced upwelling of cooler water at the shelf break. The proximity of the continental shelf to the north makes the nearshore region at the northern extent of the ecosystem accessible to penetration of low-salinity coastal flows from the north during strong southward wind events typical of fall. Cross-shelf subsurface intrusions of cooler upwelled waters from the Florida Current are also possible during summer as the shelf stratifies from summer heating combined with both wind and eddy-induced upwelling. In this area of the shelf, the Florida Current is less confined by the Florida Straits channel. The growth of frontal eddies along the Florida Current can undergo explosive growth, causing large onshore transports of upwelled waters and new nutrients that support primary production.

Climate, Waves, and Tides

The climate of southeast Florida is classified in the Köppen Climate Classification System (Trewartha, 1968) as tropical savanna, characterized by a pronounced dry season. Air temperatures average 19.0°C in the winter and 28.2°C in summer, with an overall average of 24°C. Water temperatures are moderated by the proximity of the northward flowing Florida Current, an arm of the Gulf Stream passing through the Straits of Florida. The minimum water temperature measured offshore Broward County during the three-year period of 2001-2003 was 18.3°C and the maximum was 30.5°C (Banks *et al.,* 2008).

During the dry season (November-March), Florida experiences the passage of mid-latitude, synoptic-scale cold fronts (Hodanish *et al.,* 1997) which bring strong winds from the northeast. These "nor'easters" usually last for two to three days. These fronts may have a significant impact on the beach ecosystem by increasing southward sediment transport (littoral transport), offshore loses of course beach sediment (with some burial of nearshore hardbottom), and shoreward aeolian transport of fine sediments which contribute to increases in dune elevation. Strong winds also generate waves which can cause a flattening of the beach profile and may form scarps on the beach berm and erosion of dunes.

In the wet season (late spring to early fall, June-September), differential heating generates mesoscale fronts, creating sea breezes. The convergence of these moisture-laden sea breezes, developing from the different water bodies (Atlantic Ocean, Gulf of Mexico, and Lake Okeechobee), coupled with high humidity in the Everglades, can result in low pressure troughs developing across the Florida peninsula. This leads to intense thunderstorm activity, which moves from inland to the coasts, delivering large amounts of freshwater to the coastal shelf. South Florida receives 70 percent of its annual rainfall during these months. Trewartha (1968) referred to the daily sea breeze circulation as a "diurnal monsoon." The typical wind direction during most of the southeast Florida wet season is from southeast (tropical). During these times, winds tend to be relatively light and cause little beach erosion.

From June through November, Florida is a prime landfall target for tropical cyclones, although storms have been documented as early as March and as late as December. Hurricanes and tropical storms affect beach ecosystems similar to that of winter storms, except alteration of the physical environment is magnified because of stronger winds with the added impact of high water levels caused by storm surge. Because winds in a hurricane shift in direction as the storm passes, longshore sediment transport direction can shift. In the 100-year period from 1899-1999, the region was hit by 27 hurricanes, or about once every four years. Half of these storms were classified as category 3 or higher (Neumann *et al.,* 1999).

The waves in southeast Florida are influenced by the shadowing effect of the Bahamas and, to a lesser extent, Cuba. In the northern part of the southeast Florida region, swells from the north are of relatively high energy since they are not influenced by the shallow Bahamas Banks. Broward and Miami-Dade counties are less affected by this wave energy because of the shadowing effect of the Bahamas Banks.

In winter, low pressure systems form on the Atlantic Ocean coast of the U.S. Short-period, wind-driven waves develop near the center of these lows. As these seas move away from the center of low pressure, they can develop into long period swells, locally known as "ground swells" that may affect southeast Florida. Long-period swells result in increased sediment suspension and turbidity in nearshore waters. Hanes and Dompe (1995) measured turbidity concurrently with waves and currents in situ at depths of 5 m and 10 m offshore Hollywood, Florida (Broward County) from January 1990 to April 1992. They found a significant correlation between wave height and turbidity. In addition, there was a threshold wave height (0.6 m), below which waves did not materially influence turbidity.

Tides in the region are semi-diurnal with amplitudes of approximately 0.8 m. Tidal forces influence coastal circulation near navigation inlets. Nine navigational inlets, approximately 16 km apart, are maintained in southeast Florida. At the southern extent of the region, tidal passes allow the exchange of water from Biscayne Bay onto the coastal shelf. The relative contribution of the inlets to coastal circulation can be estimated by comparing inlet tidal prisms (the volume of water exchanged in the estuary between high and low tide). Coastal circulation is affected by the tidal prism, inlet dimensions, shelf width at the inlets, offshore distance of the Florida Current, tidal plume constituents, and salinity. The salinity of the plumes discharging from the inlets is significantly different in the wet season compared with the dry season.

Connectivity

Conditions in the ecosystem are influenced by interactions with the strong northward flowing Florida Current at the shelf break and by freshwater inflows from one of the most densely populated urban areas in the U.S. The Florida Current connects outflow from the eastern Gulf of Mexico (the Loop Current) with the Gulf Stream in the North Atlantic (Figure 5). The Straits of Florida lie between the Florida southeast coast and the Bahamas and forms a conduit for the Florida Current. The Florida Current is made up of about equal parts of waters originating in the South Atlantic and North Atlantic subtropical gyres (Schmitz and Richardson, 1991; Wilson and Johns, 1997) and is, therefore, an important link in both the North Atlantic Sverdrup circulation (Leetmaa *et al.,* 1977) and the global thermohaline circulation (Gordon, 1986). The upper layer waters of the Florida Current with temperatures greater than 24°C are derived primarily from the South Atlantic (Schmitz and Richardson, 1991) and are transported across the equator and through the Caribbean by the combined influence of the North Brazil Current and the North Atlantic wind-driven subtropical gyre.

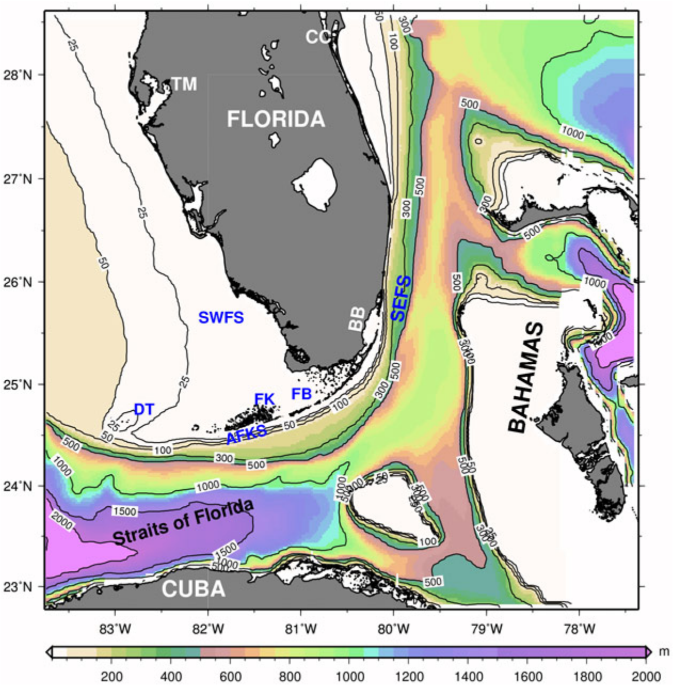


Figure 5. Bathymetry of the Straits of Florida and south Florida shelf areas. The Southeast Florida Shelf (SEFS) extends from Biscayne Bay (BB) to St. Lucie estuary near 27°N; the Atlantic Florida Keys Shelf (AFKS); Southwest Florida Shelf (SWFS); Florida Bay (FB); and Dry Tortugas (DT).

Interaction between the Florida Current and shallow inshore waters is driven by a continually-evolving stream of frontal meanders and eddies that form along the current's western edge. These features influence characteristics of the water column at the offshore boundary of the coastal marine ecosystem. Eddies form in a couple of ways. Some that have their origin in the Loop Current can carry water from distant sources, such as the plume at the mouth of the Mississippi River (Ortner *et al.,* 1995). Eddies are also generated along the southeast Florida coast by the interaction of the Florida

Current with the topography of the Florida shelf (Lee, 1975; Lee and Mayer, 1977; Shay *et al.,* 1998; Lee *et al.,* 1991).

The movement of eddies downstream (north) along the outer Florida shelf drives an exchange of water masses between the Florida Current and the adjacent shelf (Figure 6). Upwelling in the core of an eddy can inject nutrient-rich water from depths along the shelf slope up into the euphotic zone, stimulating primary production and other changes in the water column. Variations in current and temperature at the boundary of the coastal marine ecosystem reflect the passage of eddies that occur at the average frequency of once per week throughout the year, with little seasonal change. Eddy passages normally take one to two days and result in considerable exchange between the resident shelf waters and new water from within the eddy. Displacement of shelf waters by eddies at an average weekly interval represents a flushing mechanism and mean residence time of shelf waters, outside the ecosystem, of approximately one week.

Human Population

South Florida experienced a rapid change in economic and demographic factors within the last century. Florida was the only state in the U.S. to grow from a population of less than one million at the start of the 20th century to a population of over 10 million by the century's end (Hobbs and Stoops, 2002). Most of this population growth happened in the five southern counties adjacent to coral reefs (Palm Beach, Broward, Miami-Dade, Monroe, and Collier) (Figure 7). In 2030, southeast Florida will have a population of 8.5 million, 2.9 million more than in 2010 (Bureau of Census, 2010). The population size of South Florida influences many regional- and local-scale *Drivers* like coastal development, agriculture, wastewater, fishing, and boating.

Martin County

Martin County is on the southeast coast of Florida bordering the Atlantic Ocean, between Jupiter and St. Lucie Inlet. In 2010, 146,318 people lived in the county, 15.4 percent more than lived there in 2000. About 10 percent of county residents live in Stuart, which is by far the largest incorporated municipality. Other municipalities include Jupiter Island, Ocean Breeze Park, and Sewall's Point. The University of Florida, Bureau of Economic Research projects that the population will grow by 8 percent by 2020.

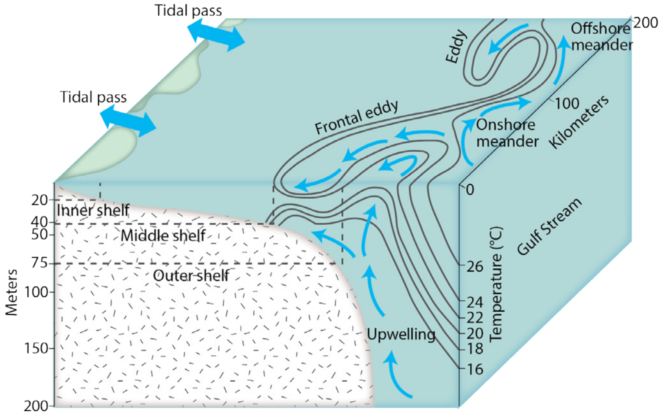


Figure 6. Schematic of Gulf Stream frontal eddies and meanders, together with shelf flow regimes on the southeast U.S. shelf.

Palm Beach County

Palm Beach County is on the southeast coast of Florida bordering the Atlantic Ocean, between Jupiter and Boca Raton. In 2010, 1.32 million people lived in the county, 16.7 percent more than livedw there in 2000. About half the residents live in one of 38 incorporated municipalities, most of which are clustered along the Atlantic coast. West Palm Beach and Boca Raton are the largest cities in the county, with 100,000 and 84,000 residents, respectively. The University of Florida, Bureau of Economic Research projects that the population will grow by 7.2 percent by 2020.

Broward County

Broward County is on the southeast coast of Florida bordering the Atlantic Ocean, between Boca Raton and Hallandale Beach, north of Miami. In 2010, 1.75 million people lived in the county, 7.7 percent more than lived there in 2000. Nearly all of the residents live in one of 31 incorporated municipalities clustered in the eastern third of the county, along the Atlantic coast. Fort Lauderdale and Pembroke Pines are the largest cities in the county, with 166,000 and 155,000 residents, respectively. The University of Florida, Bureau of Economic Research projects that the population will grow by 4.3 percent by 2020.

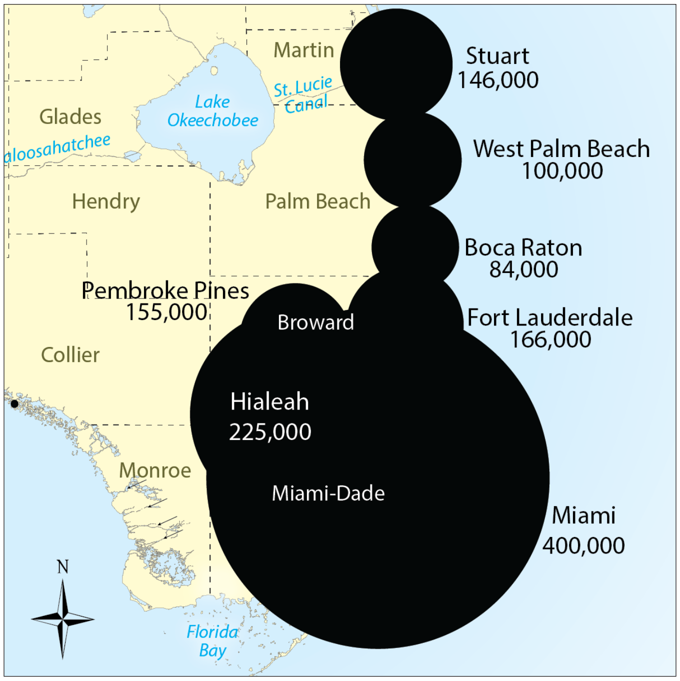


Figure 7. Population centers along the southeast Florida coast (Bureau of Census, 2010).

Miami-Dade County

Miami-Dade County is on the southeast coast of Florida bordering the Atlantic Ocean, between Hallandale Beach and the Florida Keys. In 2010, 2.5 million people lived in the county, 10.8 percent more than lived there in 2000. About half of the residents live in one of 35 incorporated municipalities, most of which are clustered along the Atlantic coast. The urbanized area of south Miami-Dade County is unique in the U.S. for bordering on two national parks, Everglades and Biscayne, and the Big Cypress National Reserve. The University of Florida, Bureau of Economic Research projects that the population will grow by 6.7 percent by 2020.

The Miami urbanized area (as defined by the Census Bureau) encompasses the contiguous urbanized coastline of Palm Beach, Broward, and Miami-Dade counties from Jupiter south to Florida City. In 2010, 5.7 million people lived in this area (Bureau of Census, 2010). In 2008, it became the fourth largest urbanized area in the U.S., behind New York City, Los Angeles, and Chicago. The ports of Miami and Fort Lauderdale are the busiest cruise ship passenger ports in the world in both passenger traffic and cruise lines. The Miami region is one of the largest tourist destinations in Florida and the U.S.

The Southeast Florida Coast Integrated Conceptual Ecosystem Model

Conceptual Diagram: Picturing the Ecosystem

The first step in the systematic MARES process is to develop a conceptual diagram of the ecosystem (here a cross-section and a plan view of the coast) that identifies the main components of the ecosystem, the processes operating upon it, and the factors affecting its condition (Figures 8 and 9). The SEFC ecosystem consists of coral and hardbottom habitats of the reef, seagrass beds in the south, beaches and mangroves along the shoreline, as well as the overlying water column and the fish and shellfish that move among these habitats (see appendices for more information).

The degradation of beaches and coral and hardbottom habitats are major concerns for the SEFC because these reduce ecosystem services that residents rely upon, including services that support beach activities, diving and snorkeling, recreational and commercial fishing, and tourism. Local factors that affect the ecosystem and its services are fishing, diving, and other uses of the marine environment, land-based sources of pollution, and marine construction. Regional factors that affect the ecosystem include the growing urban population, agriculture, regional water management, and nutrient inputs to the water column, while global factors include climate change and the related processes of ocean acidification and accelerated sea-level rise. The application of the DPSER framework leads to the construction of narratives of the processes that sustain and change the ecosystem based on elements identified in the conceptual diagram.

Applying the Model in the Southeast Florida Coast: Coral Reef Conservation Program

To illustrate how elements of the MARES DPSER model can be used to organize an analysis of ecosystem management issues along the SEFC, consider the development and implementation of the Local Action Strategy by the state's Coral Reef Conservation Program. Florida's coastal waters contain a substantial proportion of the United State's coral reef ecosystems. Coral reef ecosystems are defined by their

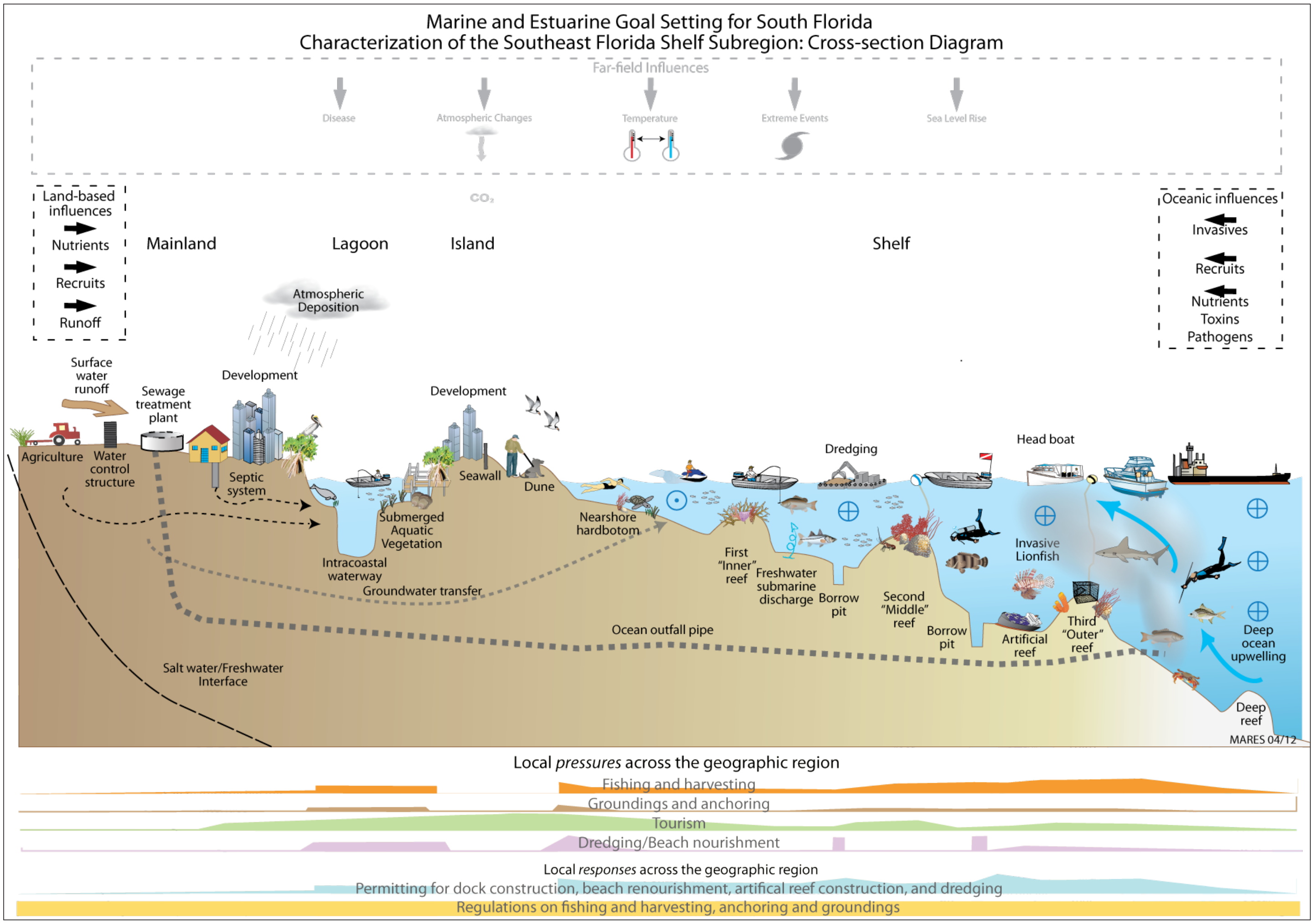


Figure 8. Southeast Florida coast integrated conceptual ecosystem model—cross-sectional diagram.

distinctive benthic habitat and by associated communities of fish and shellfish and the conditions required in the water column to sustain these, e.g., low nutrients and clear water. In the ICEM model based on the DPSER framework (Figure 10), the benthic habitat formed by the coral reef, fish and shellfish communities, and overlying water column are elements included in the *State* component of the SEFC coastal marine ecosystem.

Florida's coral reefs are a valuable local and national resource. People come to South Florida to enjoy the subtropical climate and the services its ecosystems provide and, for the vast majority, this means the coastal marine ecosystem. People come to southeast Florida to enjoy its beaches, to fish or dive on coral reefs, and engage in a variety of other water-based activities. These benefits are the *Ecosystem Services* provided by the SEFC coastal marine ecosystem. Recreational activities on the southeast Florida reef tract are a major component of the South Florida economy, accounting for $3.8 billion during the period 2001-2003 (Johns *et al.,* 2001, 2004). Sustaining the *Ecosystem Services* that support this economic activity depends on maintaining the *State* of the coastal marine ecosystem.

Coral reef ecosystem health is in decline (Wilkinson, 2002, 2008; Keller *et al.,* 2009). This threatens a reduction in the benefits that people receive. This has generated widespread concern that, in 1998, resulted in the formation of the U.S. Coral Reef Task Force to coordinate a *Response* to this decline by federal, state, and local agencies. Preservation and protection of these ecosystems is the mandate for the U.S. Coral Reef Task Force, of which Florida is one of the seven states, commonwealths, and territories that are members of the task force. In southeast Florida, the result of the work of

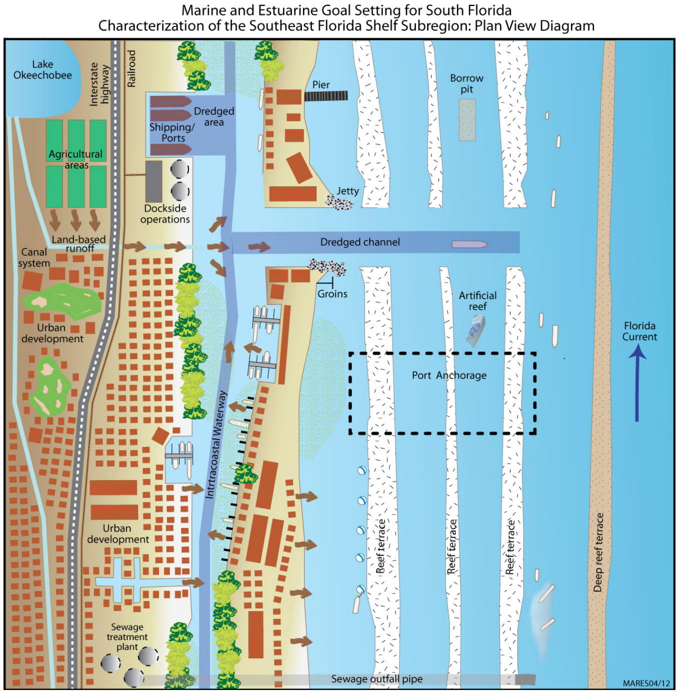


Figure 9. Southeast Florida coast integrated conceptual ecosystem model—plan view diagram.

the Task Force has been to formulate a Local Action Strategy for the purpose of preserving and managing the reef. The Southeast Florida Coral Reef Initiative (SEFCRI) guides the implementation of the Local Action Strategy with leadership provided by the Coral Reef Conservation Program (CRCP), a program of the Florida Department of Environmental Protection. SEFCRI consists of an interagency team of marine resource professionals drawn from federal, state, and local agencies, universities, and industry.

The Local Action Strategy consists of a number of projects and activities designed to mitigate *Pressures* causing change in the coastal marine ecosystem and to restore the *State* of the coral reef, where this is possible. Intensive development of the SEFC, intensive use of its coastal waters, and phenomena related to global climate change are recognized as the underlying *Drivers*. The work of SEFCRI and the CRCP is focused in four main areas related to major *Pressures* affecting the reef: (1) land-based sources of pollution; (2) impacts of the maritime industry and coastal construction; (3) impacts of fishing, diving, and other activities on the reef; and (4) promoting sustainable use through awareness and appreciation by the public.

Drivers and Pressures: Sources of Change

It is useful to distinguish between *Pressures* arising from far-field causes and those arising from near-field causes. The distinction between far-field and near-field pressures has practical implications in deciding how to respond to the resulting changes in the ecosystem. Far-field pressures alter environmental conditions at the boundary of the ecosystem, and their effects propagate through the ecosystem. Far-field pressures of concern in the SEFC region include *Pressures* related to climate change and the rising concentration of carbon dioxide in the atmosphere, including the effects of ocean acidification and accelerated sea-level rise. Near-field pressures are generated internally, and their effect varies in intensity across the ecosystem. At the scale of the South Florida region, agricultural, municipal, and regional water management practices affect water quality and other characteristics of nearshore, coastal water. Locally, human activities in southeast Florida impose their own set of pressures on the surrounding marine environment. Near-field pressures of concern include the effects of land-based sources of pollution, maritime industry, coastal construction, and intensive use of the reef for fishing, diving, and other activities. Concern is growing over the impact of the lionfish, an invasive species, on native fisheries.

Far-Field Drivers and Pressures

Although far-field factors are outside the realm of management control within the SEFC, it is important that the general public and decision-makers are aware of their influence so they can understand the impact of management actions against the broader suite of *Pressures* acting upon the ecosystem (Table 1). Global processes that influence the SEFC will be particularly difficult to manage given that global treaty agreements or global behavioral changes are required for a *Response* that can effectively mitigate the *Pressure*. The most prevalent global driver that produces direct impacts on the SEFC is climate change related to the rising concentration of carbon dioxide in the atmosphere. Resulting changes in salinity, temperature, and aragonite saturation state of the water column will affect the health of marine organisms by changing the efficiency of their physiological processes. The impact of ocean acidification on marine organisms is highly variable, although it

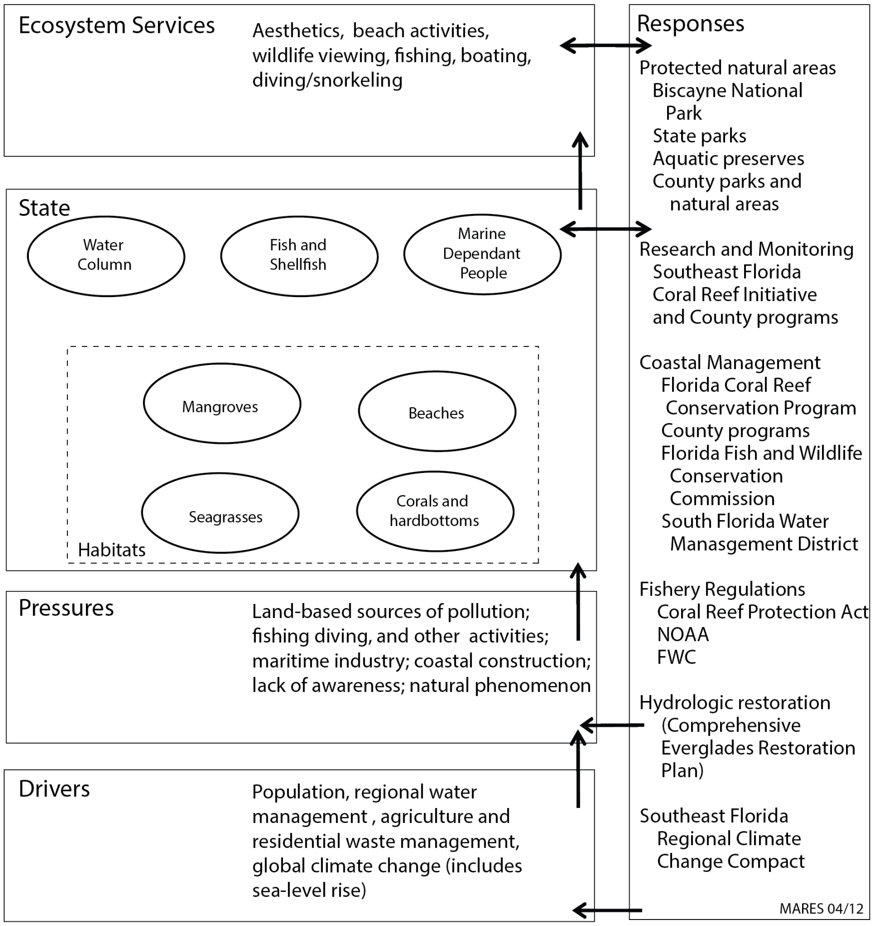


Figure 10. Integrated conceptual ecosystem model based on the DPSER framework.

appears unlikely that effects will be dramatic in the short-term (Hendriks *et al.,* 2010). However, changes due to temperature increases could be more pronounced because many organisms in southeast Florida are already living near their thermal maximums (Manzello *et al.,* 2007).

Ocean Acidification

Increasing concentrations of carbon dioxide (CO_2) in the atmosphere and the ocean affect the chemistry of ocean waters. Roughly 30 percent of the anthropogenically-released CO_2 has been absorbed by the global oceans (Feely *et al.,* 2004). An increased concentration of CO_2 lowers the pH of seawater, i.e., making it more acidic, and decreases the saturation state of aragonite. This has the detrimental effect of making it more difficult for marine organisms, like corals, to build and support their skeletal structures (Andersson *et al.,* 2005; Kleypas *et al.,* 2006; Manzello *et al.,* 2008; Cohen and Holcomb, 2009). An increased concentration of CO_2 and HCO_3^- (bicarbonate) also increases seagrass production (Hall-Spencer *et al.,* 2008), leaf photosynthetic rates (Zimmerman *et al.,* 1997), and plant reproductive output (Palacios and Zimmerman, 2007). However, because acidification will occur relatively slowly, allowing some organisms to adapt, and interactions among different ecosystem components are complex (Hendriks *et al.,* 2010), it is not yet clear what effects acidification will have on the coastal marine ecosystem of South Florida.

Accelerated Sea-Level Rise

The SEFC is situated at a low elevation and is vulnerable to sea-level rise. The global phenomenon of climate change and accelerated sea-level rise alters the relative position of sea level, tides, and currents along the SEFC. The existing geomorphology of the barrier island coastline, with mangrove-lined lagoons behind, reflects the influence of a stable regime of slowly rising sea level (average rate of

4 cm/100 years) during the past ~3200 years (Wanless *et al.,* 1994). Since about 1930, the relative rate of sea-level rise has increased substantially, averaging 30-40 cm/100 years (Wanless *et al.,* 1994). As a result, significant changes have already occurred in the coastal systems unaltered by development, including increased erosion and saltwater encroachment.

Acceleration of sea-level rise is expected to continue into the foreseeable future. The "Copenhagen Report" (Allison *et al.,* 2009) states that, "For unmitigated emissions [sea-level rise] may well exceed 1 meter" by 2100, with an upper limit at approximately 2 meters. This revises the widely-quoted projections contained in the IPCC (2007) report, which did not take into account melting of the Greenland and Antarctic ice sheets. Accelerated sea-level rise will push marine water far into freshwater environments, resulting in a substantial loss of freshwater wetlands (on mainland South Florida) and diminished groundwater resources. Indirect impacts of sea-level rise, due to impingement of the sea on the developed coastline, may be greater than direct impacts of rising water levels on natural components of the coast. The anticipated rise in sea level and the increased likelihood of flooding in residential and commercial areas will motivate shoreline protection activities, and disturbances due to the coastal construction associated with these activities will have effects in the nearshore environment with cascading effects further offshore.

Increasing Temperature

Worldwide temperatures have increased over the past century by 0.74°C. Strong thermal anomalies leading to bleaching events on coral reefs have been observed with increasing frequency since the 1980s (Baker *et al.,* 2008).

Table 1. Far-field drivers and pressures of greatest importance to the southeast Florida coast.

Driver: Climate Change	Pressure: All pressures that arise from increasing CO_2
Ocean acidification	
Sea-level rise	
Increasing water and air temperature	
Altered regional rainfall and evaporation patterns	
Changes in tropical storm intensity, duration, and/or frequency	
Driver: Water-Based Activities:	**Pressure: Recreation, fishing, tourism, commerce/shipping**
Fishing	Commercial, recreational, and subsistence
Marine debris	Ghost traps, fishing line, waste
Contaminant releases	Marine spills, pathogen shedding, disease transport
Driver: Land-Based Activities:	**Pressure: Tourism, agriculture, shelter, water management, waste management, and human population**
Changes in freshwater inflow	Quality (nutrient loading, contaminants), quantity, timing, or distribution
Contaminant releases	Septic tanks, fertilizers, industrial waste, construction debris, manufacturing, and industrial pollutants (e.g., mercury from coal plants)

It has also been demonstrated that disease outbreaks are favored by unusually warm temperatures (Bruno *et al.,* 2007). In the Florida Keys, a series of repeated bleaching and disease outbreaks have served to reduce average coral cover from near 15 percent to less than 5 percent, and losses in the dominant reef builders *Acropora palmata*, *A. cervicornis,* and the *Montastraea annularis* complex have been particularly striking (Jaap *et al.,* 2008). Many Florida Keys reefs are presently comparable in coral cover and diversity to those on the higher-latitude southeast Florida reef tract. The latter has so far escaped similar depredation of its coral populations by weather and diseases and may, therefore, constitute an important refuge for the Florida Keys reef tract populations.

The two drivers which influence seawater temperature are climate change and storms. Seawater temperatures are predicted to rise due to climate change (Twilley *et al.,* 2001). Storms, on the other hand, can lower seawater temperatures (Manzello *et al.,* 2007). Both high (>30°C) and low (<15°C) temperatures have been shown to cause coral bleaching (i.e., expulsion of symbiotic dinoflagellates) and, if prolonged, significant mortality to corals and other benthic organisms (van Oppen and Lough, 2009). Coral bleaching and mortality in the Florida reef tract have been recorded during the 1998 and 2005 bleaching events. Cold-water mortality of corals and other organisms was observed historically (Davis, 1982; Jaap and Sargent, 1994) and, more recently, in the winter of 2010 (Lirman, personal observation).

Frequency and Intensity of Tropical Storms

The "IPCC Summary Report for Policymakers" (2007, p. 12) states that "it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical SSTs" [sea surface temperatures]. The "Copenhagen Report" (Allison *et al.,* 2009) discusses evidence that hurricane activity has increased over the past decade, and the number of category 4 and 5 hurricanes has also increased globally. An increase in tropical storms promises increased rainfall over land and increased mixing of shallow surface waters of the Florida Shelf during the passage of these storms (e.g., Ortner *et al.,* 1984). The passage of intense storms can resuspend sediments and reduce the transparency of the water column (e.g., Chen *et al.,* 2009), resulting in a potential reduction in pelagic primary production in coastal waters.

Southeast Florida beaches can experience major hurricanes that may cause significant changes to the form of the beach and wash away large numbers of sea turtle eggs. A natural beach is resilient to the frequent coastal storms that are common to the SEFC (may occur several times each year). However, less frequent (may occur every 5-30 years) hurricanes, tropical storms, and nor'easters can significantly alter beach morphology, destroy dune vegetation, and negatively affect habitat. Where the energy-absorbing dune system has been replaced by urban development, even relatively minor storms cause some negative impact on the habitat and recreational uses of the beach, and the habitat loss (if any is present) can be permanent.

Altered Rainfall and Evaporation

The net effect that global climate change will have on rainfall and evaporation in South Florida is uncertain. The IPCC report indicates that there will be a likely decrease in precipitation over subtropical land regions and increased evaporation rates (IPCC, 2007; Allison *et al.,* 2009). However, increased temperatures are also associated with increases in the frequency of thunderstorms, particularly in the tropics and southeastern U.S. (Trap *et al.,* 2007; Aumann *et al.,* 2008). Thunderstorms are the major source of rainfall during the summer wet season in South Florida.

Near-Field Drivers and Pressures

Near-field *Drivers* and *Pressures* are related to the pressures already identified above, i.e., land-based sources of pollution, maritime industry and coastal construction, and fishing, diving, and other uses of the reef and, more generally, to agricultural and urban development in the region (Table 2). Development in South Florida during the 20th century drastically altered the coastal hydrology of the region. Water management activities, undertaken to accommodate urban and agricultural land uses, have altered the timing, distribution, quantity, and quality of freshwater inflows to coastal waters. The large urban population along the southeast coast relies on the adjacent coastal marine environment for disposal of treated wastewater, mostly through outfalls in deeper water, away from the shoreline.

Urban and Shoreline Development

Urban development along the SEFC has altered the shoreline and disrupted natural processes that contribute to maintaining shoreline habitats. *Drivers* of change on the South Florida shoreline range over relatively large temporal and spatial scales, from localized overuse to very large spatial scale sea-level rise (Defeo *et al.,* 2009; Schlacher *et al.,* 2007). Coastal engineering projects and urban development permanently impact the beach over tens of kilometers; impacts from climate change continue for millennia over larger spatial extents. Recreation, nourishment, and pollution impact beaches at temporal scales of weeks to years and over spatial scales of 10-100 kilometers (Defeo *et al.,* 2009).

The pre-development shoreline of southeast Florida was typical of the barrier island complexes of north and central Florida. Inlets associated with river drainage (e.g., Jupiter Inlet/Loxahatchee River, New River/New River Inlet in Fort Lauderdale) were open much of the time. Many other inlets were ephemeral, frequently changing locations or periodically opening and closing, the dynamics of which were controlled by inland water discharge, wind patterns, and offshore storms.

As coastal development and commerce increased in southeast Florida, a need arose for stable navigational inlets. The implemented solution installed rock jetties at desired locations and dredged channels from inland water through the barrier islands to the ocean. The construction of jetties interrupted the littoral sediment drift process, and down-drift beaches have been starved of their sediment supply. Some of the barrier islands/spits subsequently migrated shoreward (west) until they were welded to the mainland shoreline whose position is fixed by underlying rock formations. A prime example of a natural beach becoming beach eroded by inlet jetties is at Port Everglades in Broward County.

There are numerous federal, state, county, city, and non-government organization owned beachfront parks in the southeast Florida region. Most of these areas were designed to protect the remaining coastal flora and fauna, provide access to the public, facilitate beach restoration, or a combination of these purposes. However, the majority of beachfront

Table 2. Near-field drivers and pressures of greatest importance to the southeast Florida coast.

Water-Based Activities:	Recreation, fishing, tourism, commerce/shipping
Fishing	Commercial, recreational, and subsistence
Groundings	Benthic habitat/community destruction, propeller scars, anchor damage
Dredging	Damage to bottom benthic habitat/community destruction, sedimentation, and altered circulation
Marine debris	Ghost traps, fishing line, waste
Noise	Boating, military, oil exploration, and drilling
Invasive species	For example, lionfish
Contaminant releases	Marine spills, pathogen shedding, disease transport
Land-Based Activities:	**Tourism, agriculture, shelter, water management, waste management**
Alteration of shorelines	Shoreline hardening, increased impermeable surface area, loss of wetlands, dredging
Changes in freshwater inflow	Quality (nutrient loading, contaminants), quantity, timing, or distribution
Contaminant releases	Septic tanks, fertilizers, industrial waste, construction debris, manufacturing and industrial pollutants (e.g., mercury from coal plants)

parks in the southeast Florida region were developed to accommodate parking for public access to the beach. As a result, the development, operation, and maintenance of beach parks have resulted in a significant loss of the natural aspects of the coastal landscape and an increased use of the beach for recreation.

Regional Water Management

Potable water needs in Miami-Dade, Broward, and southeastern Palm Beach counties are primarily met by withdrawing water from the surficial Biscayne Aquifer, whose waters are derived from local rainfall and, during dry periods, from canals ultimately linked to Lake Okeechobee (Carriker, 2008). Agriculture water needs and flood control issues, as well as groundwater control (e.g., saltwater intrusion, phosphorus reduction), have been addressed through construction of an extensive canal system (SFWMD, 2010). In addition, an Intracoastal Waterway extends 374 miles along the southeast coast, from Fernandina Harbor to Miami Harbor (Florida Inland Navigation District, 2000). The Intracoastal Waterway enhances the north-south movement of water through the lagoons behind the barrier island coastline.

Inlets must be considered as major sources of land-based pollution. For northern Miami-Dade, Broward, and Palm Beach counties, surface waters flowing into the ocean, including canal and Intracoastal Waterway waters, are predominantly constrained to a series of inlets: Norris Cut, Bear Cut, Government Cut, Haulover Inlet, Port Everglades Inlet, Hillsboro Inlet, Boca Raton Inlet, Boynton Inlet, and Palm Beach (North Lake Worth) Inlet. In a 1998 study of water quality in South Florida, the U.S. Geological Survey listed domestic wastewater facility discharges (1500 facilities), industrial wastewater discharges (including leachage and runoff from contaminated land), septic tank discharge (nearly a half-million), agricultural wastewater runoff (citrus farming, dairy and beef operations), runoff from landfills (40 active landfills), and urban wastewater (stormwater) runoff as the leading categories of land-based pollution (Marella, 1998). Anthropogenic materials from inlets have been implicated in bloom activity on coral reefs (Lapointe and Bedford, 2011).

Treated-wastewater outfalls are point sources of anthropogenic materials (EPA, 1992). There are five treated-wastewater outfalls continuously operating in southeast Florida; their combined flow in 2011 was 199 millions gallons per day (Carsey *et al.,* 2012). The number of ocean outfalls has decreased significantly over the years; there were ten operating in 1972 (Lee and McGuire, 1972). Current legislation (Leah Schad Memorial Ocean Outfall Act) requires termination of ocean outfalls for routine effluent discharge by 2025 and requires that a majority of the wastewater previously discharged be beneficially reused (FDEP, 2010). This, however, presents a significant challenge to municipalities who must design, finance, and implement these alternative systems.

A significant transport of water to the coastal ocean is through submarine groundwater discharge, now recognized as a major vector of anthropogenic materials and thus an area of growing interest and concern, due to activities such as wastewater disposal from septic systems and agricultural and urban uses of fertilizers (Howarth *et al.,* 2003; Lapointe *et al.,* 1990; Finkl and Charlier, 2003; Paytan *et al.,* 2006). Submarine groundwater discharge is an efficient transport of nutrients; it has been estimated that nitrates from submarine groundwater discharge sources in west-central Florida may exceed that of rivers and atmospheric deposition (Hu *et al.,* 2006). Finkl and Krupa (2003) estimated that groundwater fluxes of nutrients to Palm Beach County averaged 15,690 kgN/d and 1134 kgP/d, more than double that of surface water fluxes (6775 kgN/d and 540 kgP/d).

Changes in salinity, in either direction, due to altered freshwater discharge to the coast, can lead to increased or decreased respiration depending on the coral species (Vernberg and Vernberg, 1972). Reduced salinity can also lead to local coral bleaching (Brown, 1997). It is generally agreed that most scleractinian corals can survive only small variations in salinity, with death resulting when salinity drops below 25 percent or increases above 40 percent (Edmondson, 1928; Jokiel *et al.,* 1974). While mean terrestrial runoff may decline in the future as the result of climate change, stormwater delivery and pulsed runoffs that tend to bring pollutant and nutrient pulses to reefs may indeed increase. Heavy rainfall can lead to the outflow of freshwater, reducing the salinity around the inlets. Changes in atmospheric heat content are predicted to change global rainfall patterns, leading potentially to increased dryness in Florida. This would, however, be counteracted by increased moisture content of the tropical atmosphere, delivering more precipitation associated with cyclonic disturbances.

Land-Based Sources of Pollution

Pollution impacts caused by human activities are associated with oil spills (Jackson *et al.,* 1989), urban and agricultural stormwater and overland runoff (Glynn *et al.,* 1989; Jones, 2005; Fauth *et al.,* 2006), and physical impacts caused by solid waste disposal and others causes (Peters et al., 1997). Increased nutrients can have both direct and indirect impacts on benthic organisms (Szmant, 2002). Direct impacts include the impairment of calcification and growth in stony corals under high nutrient conditions (Koop *et al.,* 2001). Indirect effects include the disruption of the coral-zooxanthellae symbiosis and a reduction in the translocation of carbon to the host (Fabricius, 2005), increased phytoplankton in the water column leading to reduced light penetration and even toxicity (Brand and Compton, 2007; Butler *et al.,* 2005; Boyer *et al.,* 2009), and enhanced growth of macroalgae, a competitor for space in coral reefs and hardbottom habitats (Lapointe and Clark, 1992; Lapointe *et al.,* 2002, 2004).

The addition of nutrients from land-based sources, on top of the natural source of nutrients from upwelling along the shelf margin, stimulates the occurrence of harmful algal blooms. Wastewater discharge and agricultural runoff are the two largest sources of nutrients from land-based sources. A bloom occurs when an alga rapidly increases in number to the extent that it dominates the local planktonic or benthic community (Kirkpatrick *et al.,* 2004). Harmful algal blooms in southeast Florida are primarily composed of the dinoflagellate, *Karenia brevis*, which contains a brevetoxin compound that can aerate and cause respiratory distress. It can also cause paralytic shellfish poisoning via consumption of contaminated shellfish from an area with a recent *K. brevis* bloom (Kirkpatrick *et al.,* 2004). Large blooms of *K. brevis* may result in hypoxic conditions (low dissolved oxygen) fatal to many species (Hu *et al.,* 2006).

A related problem is in macroalgal blooms. The macroalgae in southeast Florida waters include *Dictyota* ssp. and *Halimeda* ssp. (Banks *et al.,* 2008). Macroalgal blooms are usually associated with non-indigenous species such as *Lyngbya, Caulerpa,* and *Codium* ssp. (Collier *et al.,* 2008). These blooms are harmful not through chemical toxicity but through disturbance of the ecosystem, crowding out other species (Collier *et al.,* 2008). Blooms may be related to a variety of causes including increased nutrient availability or removal of macroalgal grazers ("bottom up" versus "top down" control) (Valiela *et al.,* 1997).

Toxification can result from wastewater or from phytoplankton blooms. The following chemicals commonly found in wastewater induce toxic effects on corals and other reef organisms: polychlorinated biphenyls, metals, chlorine, phosphate, pesticides, and petroleum hydrocarbons (Pastorok and Bilyard, 1985). Cyanobacteria blooms can be directly toxic to corals and indirectly affect them by stimulating the growth of bacteria. This can lead to corals suffering from black band disease (Gantar *et al.,* 2009). In southeast Florida, a bloom by the cyanobacteria *Lyngbia* spp. caused significant coral mortality. Toxins from phytoplankton can be carried up the food web by zooplankton and even lead to the death of fish, whales, dolphins, and sea birds, changing the community surrounding the coral reefs (Steidinger, 1983; Burkholder *et al.,* 1995; Anderson and White, 1992; Gerachi *et al.,* 1989; Work *et al.,* 1993).

Maritime Industry

Southeast Florida is home to three major ports: Port Everglades, Port of Miami, and the Port of Palm Beach. Port Everglades is one of the most active cargo ports in the U.S. and South Florida's main seaport for petroleum products like gasoline and jet fuel. In 2009, Port Everglades opened the world's largest cruise terminal, overtaking the Port of Miami as the most important cruise passenger port of the world (Broward County, 2011). The Port of Miami is planning to dredge its harbor deeper to minus 50 feet to accommodate the new, larger class of Panamax vessels able to use the enlarged Panama Canal locks. This will increase trade with East Asia, resulting in a doubling of the cargo output of this port (Johnson, 2010). The Port of Palm Beach is an export port and the fourth busiest container port in Florida. It also has a cruise ship based at the port, the Bahamas Celebration cruise (Port of Palm Beach District, 2011).

The physical damage caused by vessel groundings is a major source of disturbance to shallow habitats found within and adjacent to busy shipping lanes. In Florida, impacts by large and small vessels to coral reefs are a significant source of coral mortality and reef-framework modification (Lutz, 2006; Lirman *et al.,* 2010). Damage to coral reefs can range from superficial, where only the living surfaces of corals are damaged, to structural where the geomorphologic reef matrix is fractured and exposed (Lirman *et al.,* 2010). Fishing gear impacts have been documented for both coral reefs and hardbottom communities. These impacts include the removal of sponges and soft corals by drag nets, as well as trap and line impacts on reef organisms (Ault *et al.,* 1997; Chiappone *et al.,* 2005).

Coastal Construction

Coastal construction includes dredging for harbors, laying of pipes and cables on the seafloor, and restoration of eroded beaches. Dredging causes direct physical damage to benthic habitat on the reef, as well as increased sedimentation. Since virtually the entire coastline of the southeast Florida region is built up and artificially hardened in many places, movements of sediment have been significantly altered. This has caused problems to nearshore hardgrounds both by smothering due to altered sedimentary movements and the requirement for beach renourishment that tends to lead to significant impacts by turbidity and smothering by newly-introduced sediments. Turbidity influences the amount of light that corals receive. Aller and Dodge (1974) and Dodge *et al.* (1974) discovered that coral growth slows down when water becomes more turbid, while other scientists have concluded that turbidity does not prohibit or even increase coral growth (Roy and Smith, 1971; Maragos 1974a, 1974b). A study conducted in the Florida Keys found that the coral cover was less in more turbid water (Yentsch *et al.,* 2002). Sedimentation can impact coral reef and hardbottom organisms through light reduction, smothering and burial, and toxicity (Bastidas *et al.,* 1999; Fabricius, 2005). Reductions in coral growth, photosynthesis, reproductive output, lesion regeneration, feeding activities, and recruitment have all been documented for corals under high sediment loading (Rogers, 1983, 1990; Riegl, 1995; Babcock and Smith, 2000; Lirman *et al.,* 2003; Philipp and Fabricius, 2003). Sedimentation tends to be increased by artificial alteration of shorelines and coastal construction activities.

Fishing, Diving, and Other Uses of the Reef

Fishing is a very popular recreational and important commercial activity in southeast Florida. Fishing and harvesting activities, both recreational and commercial, are key components of the economy (Johns *et al.,* 2001). The removal and collection of marine organisms has both direct and indirect impacts. Direct impacts include the targeted removal of organisms such as fish, sponges, lobsters, shrimp, anemones, live rock, and others. For example, the removal of predators may result in an increase in the abundance of damselfish that can result in increased coral mortality. This is due to their territorial activities that include killing coral tissue to grow macroalgae (Kaufman, 1977). Another cascading effect of predator removal, in this case lobsters, may be the increase in the abundance of corallivorous gastropods (*Coralliophila abbreviata*) that cause significant tissue mortality on colonies of reef-building corals and are known prey items for this once abundant taxon (Johnston and Miller, 2007). Indirect impacts include physical disturbance associated with harvesting activities, fishing and collecting gear, boating, pollution, and modifications to the trophic structure through removal of key organisms that can have cascading impacts on benthic communities. Fishing gear impacts have been documented for both coral reefs and hardbottom communities. These impacts include the removal of sponges and soft corals by drag nets (Ault *et al.,* 1997), as well as trap and line impacts on reef organisms (Chiappone *et al.,* 2005).

Other Pressures: Disease and Invasive Species

Diseases in the coastal marine environment are caused by increased pathogen and toxin concentrations in the water column, and they can infect both humans and marine life. With respect to threats to human health, even the perception that dangerous levels of pathogens or toxins are present in the water column affects *Ecosystem Servic*es such as swimming, diving, and consumption of marine life (Abdelzaher *et al.,* 2011). Diseases have been implicated as one of the main causal factors in the drastic decline in the abundance and distribution of corals recorded over the past three decades in Florida and elsewhere (Aronson and Precht, 2001; Kim and Harvell, 2002; Richardson and Voss, 2005). Many (if not most) of the epizootic agents and transmission pathways that affect soft and hard corals and sponges have not been fully described. Nevertheless, studies have found that increased temperatures are related to disease prevalence (especially after bleaching events, Brandt and McManus, 2009), human pathogens may cause disease in nearshore corals (Sutherland and Ritchie, 2004), and that the predatory and territorial activities of snails, polychaete worms, and fish may be a mechanism for inter-colony transmission of diseases vectors (Williams and Miller, 2005).

Invasive species can alter the ecosystem balance of a region. In South Florida, the invasive lionfish is a major threat to coral reef communities. Many adults and juveniles have been found, which indicates that they are established and reproducing here (Hare and Whitfield, 2003). Lionfish could impact the native ecosystem of the southeast Florida shelf through predatory interactions. Lionfish feed on a wide variety of smaller fish, shrimp, and crabs which are abundant in this area (Fishelson, 1975; Sano *et al.,* 1984; Wenner *et al.,* 1983). Predation on lionfish is thought to be limited because they only have a few predators within the native range (Bernadsky and Goulet, 1991). Moreover, predators along the southeast U.S. have no experience with the venomous spines of the lionfish (Ray and Coates, 1958; Halstead, 1965).

State: Key Attributes of the Ecosystem

The *State* of the ecosystem is defined, operationally, by attributes. Attributes are a parsimonious subset of all descriptive characteristics of the marine environment that represent its overall condition (Ogden *et al.,* 2005). The marine waters of the SEFC support a diverse ecosystem which can be divided into seven submodels that describe the coastal marine environment: (1) water column; (2) fish and shellfish; two benthic communities – (3) coral and hardbottom on the reef tract; and (4) seagrass beds, located predominantly in Biscayne Bay; and two shoreline habitats – (5) beaches; and (6) mangrove-lined lagoons. Marine-dependent people (7) must also be included as an integral part of the ecosystem. *State* submodels describe these components in detail in the appendices to this report.

Water Column

The water column submodel encompasses the physical, chemical, and biological characteristics of the water column, including sediment, phytoplankton, and zooplankton suspended in the water column. Currently, the water column of the SEFC is highly oligotrophic with low phytoplankton biomass, low nutrient concentrations, and clear water (Hitchcock *et al.,* 2005; Boyer and Jones, 2002). The water column must remain oligotrophic to support the highly valuable and characteristic benthic habitats, including seagrass, coral reefs, and hardbottom. In turn, these benthic habitats support the highly valuable and productive fish community.

Characteristics of the water column along the SEFC reflect the influence of several sources. The waters on the shallow shelf are a mixture of clear, oligotrophic tropical water, carried by the Florida Current, and nutrient-rich freshwater discharged from canals, as runoff, and as treated wastewater from the urbanized coast. Eddies that move along the edge of the Florida Current can inject nutrient-rich water from upwelling along the shelf slope, and long-lived eddies can transport nutrients, pollutants, eggs, and larvae from distant sources in the Caribbean and Gulf of Mexico. At the region's north end, near St. Lucie, the shallow southeast U.S. continental shelf is another source of nutrient-rich water.

Fish and Shellfish

The fish and shellfish populations along the SEFC resemble populations in the Florida Keys. Over 400 species of fish have been identified in surveys conducted in Palm Beach, Broward, and Miami-Dade counties. The fish and shellfish submodel includes populations that are harvested by commercial and recreational fisheries, endangered species, and the prey species. Populations of many species are seeded by larvae transported into the region from spawning areas in the Gulf of Mexico and the Caribbean (Banks *et al.,* 2008).

Individuals move throughout the region and beyond. In general, the structure of fish assemblages varies in the cross-shelf direction, with depth, and with bottom type. Deeper, outer reef sites harbor higher fish densities and more species than shallower, inner reef sites (Ferro *et al.,* 2005). Inshore hardbottom habitats contain disproportionately higher densities of juvenile fishes (Lindeman and Snyder, 1999; Baron *et al.,* 2004; Jordan and Spieler, 2006). The inshore hardbottom habitat is ephemeral due to disturbances caused by storms that can redistribute large amounts of sediment in the shallow waters. Inshore areas are also vulnerable to impacts by coastal construction activities, such as dredge and fill operations for beach renourishment. The inshore hardbottom functions as nursery habitat, and its ephemeral nature contributes to large annual fluctuations in fish populations in the region (Jordan and Spieler, 2006).

Benthic Habitats

Coral and Hardbottom

The coral reefs and hard bottom communities of the SEFC are comprised of a complex of relict Holocene shelf-edge, mid-shelf reefs, and limestone ridges (Lighty, 1977; Banks *et al.,* 2007, 2008). These pre-existing structures, along with the present-day biological/physical conditions of the SEFC, allow formation of hardbottom areas, patch reefs, and worm reefs that support rich and diverse biological communities of octocoral, stony coral, macroalgae, and sponge assemblages (Moyer *et al.,* 2003; Banks *et al.,* 2007, 2008). An estimated 19,653 km^2 of inshore area (<18.3 m water depth) exists in southeast Florida that could potentially support shallow-water coral reef ecosystems, and this represents one of the largest such areas in the U.S. (Rohmann *et al.,* 2005; Banks *et al.,* 2008).

In addition to hermatypic, accreting reefs, low-relief hardbottom communities are a key component of the coastal habitats of southeast Florida. Hardbottom habitats in the southeast Florida reef tract can be found adjacent to the mainland at depths from <1 m to >20 m. Nearshore hardbottom communities are characterized by limestone platform with local, strongly-undulating morphology consisting of lithified Pleistocene Anastasia Formation (shelly sands) or early Holocene beachrock ridges. This hardground can be covered by a thin layer of sediment and harbors a similar fauna to the shallow reefs—a sparse mixture of stony corals, soft corals, macroalgae, and sponges. As in the Florida Keys, any of these communities are found on remnant, low-profile habitats lacking significant zonation and topographical development (<1 m of vertical relief) in areas where sediment accumulation is <5 cm (Lirman *et al.,* 2003). These habitats, which can be important nursery habitats for lobsters, are characterized by low coral cover and small coral colony size (Blair and Flynn, 1999; Chiappone and Sullivan, 1994; Butler *et al.,* 1995).

Seagrasses

Extensive seagrass beds, similar to those found in Florida Bay and the Florida Keys, are found in the south portion of the SEFC, in and around Biscayne Bay. Five species of rooted aquatic vascular plants, or seagrasses, are commonly found in South Florida: turtle grass (*Thalassia testudinum*), manatee grass (*Syringodium filiforme*), shoal grass (*Halodule wrightii*), paddle grass (*Halophila decipiens*), and widgeon grass (*Ruppia maritime*). In the shallow water nearest shore, seagrasses are especially prevalent; over 90 percent of the area in water less than 10 m deep supports seagrass.

Seagrass beds are recognized as among the most productive and economically valuable of ecosystems (Zieman and Wetzel, 1980; Costanza *et al.,* 1997). The proximity of seagrass meadows to coral reef and mangrove ecosystems provides critical feeding grounds and nursery areas for species who rest on coral reefs or in mangroves as adults (Beck *et al.,* 2001). These associations are essential in maintaining the abundance of some coral reef and mangrove species (Valentine and Heck, 2005). In addition, seagrasses help maintain water quality. They trap sediments produced in other parts of the ecosystem (Kennedy *et al.,* 2010) and decrease sediment resuspension (Green *et al.,* 1997), thereby contributing to clearer water. They are also sites of active nutrient uptake to fuel their high primary productivity; nutrients taken up by seagrasses can not be used by phytoplankton and macroalgae.

Shoreline Habitats

Beaches

The beach and shoreline for this study of the southeast Florida MARES region extends from St. Lucie Inlet to Cape Florida and includes some of the most densely populated coastal areas in the world. A sandy beach of some form is present and uninterrupted for almost 100 miles in the study area except for several coquina (limestone) outcroppings and inlets. The study area is comprised of several beach types including barrier islands and spits/peninsulas, as well as oceanfront areas where the Atlantic Coastal Ridge fronts directly on the Atlantic Ocean. Many oceanfront areas have been subjected to sand nourishment projects as a response to erosion caused by natural beach and barrier island processes, sea-level rise, and development practices. The inlets that separate the sections of beach are in locations where inlets have historically existed (e.g., Jupiter Inlet) and inlets that were created by dredging, often in locations where ephemeral inlets have existed over time. All of the inlets in the South Florida study area are protected by jetties.

Mangroves

Three species of mangrove are native to Florida: red (*Rhizophora mangle*), black (*Avicennia germanans*), and white (*Laguncularia recemosa*) mangroves. Buttonwood (*Conocarpus erectus*), a mangrove associate, is also common in mangrove forests in southern Florida. Mangroves along the SEFC are found mainly as stands fringing the shoreline of Biscayne Bay and the tidal lagoons sheltered behind the barrier islands. The arrangement of the species within forest type determines the biota that occur within the mangrove forests (Lugo and Snedaker, 1974). Epiphytes and sessile invertebrates frequently grow on specialized root adaptations of mangroves (prop roots and pneumatephores) and these, plus the mangrove leaf litter, are the basis of mangrove food webs (Odum and Heald, 1975). Odum *et al.* (1982) reported 220 species of fish, 21 reptiles, 3 amphibians, 18 mammals, and 181 birds that utilize the mangroves of South Florida.

Mangrove forests provide important nursery habitat for numerous fishery species of economic importance and critical foraging habitat for adults of some of these same species (Odum *et al.,* 1982; Lewis *et al.,* 1985; Faunce and Serafy, 2006). Mangroves also provide foraging and nesting habitat for South Florida's ubiquitous fish-eating birds, as well as nesting and stopover habitat for resident and migratory passerine bird species (Odum *et al.,* 1982). Mangroves are also highly effective at sequestering carbon dioxide, nutrients, and protecting shorelines from erosion and storm surges (Odum and McIvor, 1990).

Marine-Dependent People

The SEFC ICEM includes marine-dependent people as an integral part of the coastal marine ecosystem, i.e., as a component of the *State* element in the DPSER framework. The category "marine-dependent people" includes people who are directly engaged in the coastal marine environment, for commercial fishing and for recreational uses, and people indirectly engaged by providing support services. There are three distinct but related classes of users of the coastal marine environment:

- Primary users are those individuals or groups that actively engage in activities in or on the water and that are directly dependent on the marine resource. Examples are anglers, divers, and swimmers.
- Secondary users are those one step removed from direct interaction with the marine resource, but who provide enabling support for the primary users. Examples include marina operators, dive shops, or bait and tackle shops.
- Tertiary users are those who don't directly interact with the coastal marine environment, but whose activities support the primary and secondary users in an indirect fashion. Examples include hotels, restaurants, souvenir shops, transportation, etc.

Similar designations have been used by others to identify people who depend directly on the coastal marine environment either for their livelihood or for recreation. As defined here, primary users correspond with people identified as "reef users" in the economic valuation by Johns *et al.* (2001), with the exception that the Johns *et al.* study excludes commercial fishers. The group of stakeholders identified by the Florida Department of Environmental Protection's Coral Reef Conservation Program is more inclusive. In addition to the primary users defined here, the stakeholders include management agencies at the federal, state, and local level, researchers, non-governmental organizations, port authorities, environmental consultants, teachers, and water resource managers (Jamie Monty, personal communication). In terms of sectors of the marine economy identified by Pendleton (n.d.) "marine-dependent people" correspond to Pendleton's commercial fishery sector and coastal and estuarine recreation sector combined. In addition to these, Pendleton identifies critical energy infrastructure, marine transportation, and coastal real estate as comprising the marine economy.

Marine-dependent people act as intermediaries between other components of the coastal marine environment and the provision of ecosystem services. The class of primary users includes most of the recreational users in the coastal marine ecosystem. Primary users also include commercial fishers, who harvest the seafood that constitute the provisioning service to the general human population. The activities of primary users directly impact other components of the coastal marine environment through various pressures. For example, the harvest activities of both recreational and commercial fishers have a significant effect on the species composition and population characteristics of fish and shellfish. The activities of secondary and tertiary users of the coastal marine environment support the activities of primary users. This support facilitates the provision of *Ecosystem Services*. Often, this is essential, as in the role of marinas and dive shops, in providing access for primary users into the coastal marine environment, but the activities of secondary and tertiary users generally occur away from marine waters.

Ecosystem Services: What People Care About

Ecosystem Services are the benefits that people receive from the ecosystem. They are what link people to the *State* of the ecosystem, through "attributes [of the environment] that people care about." *Ecosystem Services* have value that can be measured in a monetary, cultural, or social context, and the value of *Ecosystem Services* depends on conditions in the environment.

The MARES project identifies 12 distinct Ecosystem Services provided by the South Florida coastal marine ecosystem (Table 3). These can be categorized as cultural, provisioning, and regulating services, following the approach taken in the Millennial Assessment project (cf., Millennial Ecosystem Assessment, 2005; Farber *et al.,* 2006). In this context, "Cultural" services and goods are defined as the non-material benefits obtained from ecosystems such as spiritual and religious, recreation and ecotourism, aesthetic, inspirational, educational, sense of place, and cultural heritage. "Provisioning" services and goods are products obtained from ecosystems such as food, fresh water, fiber, biochemicals, and genetic resources. "Regulating" services and goods are benefits obtained from regulation of ecosystem processes such as climate regulation, disease regulation, water regulation, water purification, and pollination.

The importance of *Ecosystem Services* in supporting the recreation and tourism industry in the SEFC region cannot be overstated. During the 12-month period from June 2000 to May 2001, reef-related expenditures generated $505 million in sales in Palm Beach County, $2.1 billion in sales in Broward County, $1.3 billion in sales in Miami-Dade County, and $504 million in sales in Monroe County (Johns *et al.,* 2001). These sales resulted in $194 million in income to Palm Beach County residents, $1.1 billion in income to Broward County residents, $614 million in income to Miami-Dade County residents, and $140 million in income to Monroe County residents during the same time period (Johns *et al.,* 2001). Reef-related expenditures provided 6,300 jobs in Palm Beach County, 35,500 jobs in Broward County, 18,600 jobs in Miami-Dade County, and 10,000 jobs in Monroe County (Johns *et al.,* 2001).

Attributes People Care About: Linking State to Ecosystem Services

In general, people care about the sustainability of the coastal marine ecosystem. In the SEFC region, people are concerned with protecting and restoring the natural habitats, populations of native plants and animals, and sustaining ecological processes of the coastal marine ecosystem. The coastline in this region is the most densely-developed region in the state of Florida. People are attracted to this region, to live or to visit, by the natural beauty and amenities of the region's beaches and its coastal waters. Tourism and recreation power the region's economy, and these activities depend on sustaining the coastal marine ecosystem.

The attribute of sustainability requires a well-functioning, whole ecosystem in which all elements are healthy and functioning, i.e., the water column, fish and shellfish populations, and the coral and hardbottom, seagrass, and mangrove habitats. Reef fish make use of the entire mosaic of benthic habitats over their life spans. In turn, the communities of organisms responsible for maintaining these habitats require just the right combination of characteristics in the water column, i.e., temperature, salinity, clarity, and nutrient concentrations, in order to thrive.

Other "attributes that people care about" relate more directly to particular elements of the coastal marine environment. For example, characteristics of the water column, like clarity and cleanliness, i.e., the general absence of objectionable odor, nuisance, or disease-causing organisms, contributes to the aesthetic appeal of the coastal marine environment, as a whole. Good water quality is an important factor in people's enjoyment of beaches and other shoreline locations as places to visit.

People care about the size and health of fish and shellfish populations and about maintaining a variety of species in the ecosystem. Species that are important to the commercial fishery include the Caribbean spiny lobster, pink shrimp, and various species of finfish. Many species of interest for both commercial and recreational fishing and for divers and snorkelers are the large predator species. These species prey upon invertebrates and smaller individuals of their own kind. Hardbottom communities are valuable nursery areas for many invertebrates and fishes of both the patch reef and seagrass communities, providing microhabitats for many juvenile fishes.

People care about the extent and variety of healthy coral and hardbottom communities and areas to enjoy while diving or snorkeling. Coral reef systems provide protection and shelter for colorful and diverse macrofauna, including

Table 3. Ecosystem services provided by the South Florida coastal marine ecosystem.

Cultural	Aesthetic and Existence—Provide aesthetic quality of aquatic and terrestrial environments (visual, olfactory, and auditory), therapeutic benefits, pristine wilderness for future generations. Recreation—Provide suitable environment/setting for beach activities and other marine activities such as fishing, diving, snorkeling, motor and non-motor boating. Science and Education—Provide a living laboratory for formal and informal education and for scientific research. Cultural Amenity—Support a maritime way of life, sense of place, maritime tradition, spiritual experience.
Provisioning	Food/Fisheries—Provide safe-to-eat seafood. Ornamental Resources—Provide materials for jewelry, fashion, aquaria, etc. Medicinal/Biotechnology Resources—Provide natural materials and substances for inventions and cures.
Regulating	Hazard Moderation—Moderate to extreme environmental events (i.e., mitigation of waves and storm surge in the case of hurricanes). Waste Treatment—Retain storm water, remove nutrients, contaminants, and sediment from water, and dampen noise. etc. Climate Regulation—Moderate temperature and influence/control other processes such as wind, precipitation, and evaporation. Atmospheric Regulation—Exchange carbon dioxide, oxygen, mercury, etc. Biological Interactions—Regulate species interactions to maintain beneficial functions such as seed dispersal, pest/invasive control, herbivory, etc.

small shrimp, crabs, fish, and several species of lobsters. Many species, especially the larger predators, are important species for local fisheries. Hardbottom communities are valuable nursery areas for many invertebrates and fish of both the patch reef and seagrass communities, providing microhabitats for many juvenile fish. The three-dimensional structure of coral reefs provides protection from the impacts of storm waves, surge, and tides, protecting both natural shorelines and property from physical damage.

People care about seagrass beds as a popular destination for fishing and boating. Seagrass beds also protect shallow, unconsolidated sediments from erosion, and they help maintain water clarity by trapping suspended sediments and controlling the concentration of nutrients in the water column. Seagrass beds are also highly productive systems and provide habitat to a wide variety of commercial and recreational species as feeding grounds, nurseries, and refuges from predation. Their position at the base of the detrital food web provides food for various organisms.

People care about mangroves as a place to go to find a large number and variety of species of birds. Mangroves are also a component of the natural shoreline in the Florida Keys, which has few beaches compared with the southeast Florida coast. Mangroves help prevent erosion of the shoreline and provide natural protection for developed upland areas from storm tides and wave action during high water. Mangroves provide critical habitat in the life cycle of many important commercial and recreational fishes as both shelter and detritus-based food source (Estevez, 1998; Heald *et al.,* 1984; Lugo and Snedaker, 1974; Odum *et al.,* 1982).

People care about the beach and shoreline for access to the ocean, as an area to recreate, for storm protection, and for its ecological function as habitat. There are three main economic benefits attributed to the maintenance of healthy beach systems in the state (Murley *et al.,* 2003). These include enhanced property values; increased sales, income, and employment opportunities resulting from resident and non-resident spending; and expansion of the federal, state, and local tax base. As an international tourist destination, the beaches of southeast Florida contribute to the local, state, and national economies by enhancing opportunities for labor and capital and by making net contributions to the tax base of local, state, and federal governments.

Valuing Ecosystem Services

Use and non-use values and avoided costs can be estimated and used in benefit-cost analysis of management actions deemed necessary to protect the quality of the environment. For example, economic values for ecosystem services from survey-based research are reported in the documents "Socioeconomic Study of Reefs in Southeast Florida" and "Socioeconomic Study of Reefs in Martin County, Florida" (Johns *et al.,* 2001; Hazen and Sawyer, 2004). These studies provide estimates of the following values that represent the time period June 2000 to May 2001: (1) Total reef use of residents and visitors in each of the five counties as measured in terms of the number of person-days by recreation activity (fishing, diving, snorkeling, glass bottom boats); (2) Economic contribution of the natural and artificial reefs as residents and visitors spend money in each of the five counties to participate in reef-related recreation; (3) Willingness of reef users to pay to maintain the natural and artificial reefs of southeast Florida in their existing condition; (4) Willingness of reef users to pay for additional artificial reefs in southeast Florida; and (5) Socioeconomic characteristics of reef users. Economic contribution is measured by total sales, income, and employment generated within each county from residents and visitors who use the reefs. In addition, the opinions of residents regarding the existence or establishment of "no-take" zones as a tool to protect existing artificial and natural reefs are presented.

The use value of coral and artificial reefs to those who fish, snorkel, and SCUBA dive is $3.33 billion per year which includes $3.0 billion in reef-related recreation expenditures and $330 million in willingness to pay to protect the reefs in their existing condition (Johns *et al.,* 2001). Reef users would be willing to pay an additional $31 million per year to fund the development and maintenance of new artificial reefs in southeast Florida (Johns *et al.,* 2001). Southeast Florida coral and artificial reef-related recreation expenditures generated $4.4 billion in local production, $2.0 billion in resident income, and 70,000 jobs in the five-county area (Johns *et al.,* 2001; Hazen and Sawyer, 2004). The studies did not estimate the non-use value associated with the reefs of southeast Florida. However, this value is expected to be significant given the non-use values of natural resources used for recreation estimated in other studies throughout the U.S. and in Florida (e.g., Hazen and Sawyer, 2008).

A study was undertaken by the Center for Urban and Environmental Solutions at Florida Atlantic University in 2005 to better understand the economics of beach tourism in various parts of Florida (CUES, 2005). Over one-third of out-of-state visitors from 2000 to 2003 visited a beach. These visitors spent $19.1 billion in 2003, an amount equal to 3.8 percent of the gross state product, and paid about $600 million in state sales taxes. Almost one-half of the more than 500,000 jobs created in Florida by beach tourism is from spending in the region.

Response: Taking Action

The *Response* element of the MARES DPSER model encompasses the activities for gathering information, decision making, and implementation by agencies charged with making policies and taking actions to manage the coastal marine environment. *Responses* also include changes in attitudes and perceptions of the environment and related changes in individual behavior that, while perhaps less purposeful than the activities of management agencies, can have a large effect on *Drivers* and *Pressures*. Actions that have the effect of altering *Drivers*, *Pressures*, or the *State* of the ecosystem introduce a mechanism for feedback and, thus, the possibility for people to exert a degree of control on the ecosystem.

The current SEFC coastal marine ecosystem differs markedly from what existed 40 years ago. The urban area in southeast Florida has been among the most rapidly-growing areas in the U.S. during the last half of the 20th century, and it continues to grow, albeit at a reduced rate in recent years. As a consequence, there is more development, more human activity in the marine environment and, thus, potentially more *Pressures* acting to change the ecosystem away from sustainability. However, human behavior in the ecosystem has also changed over this time period. New behaviors, some manifested in new institutions, have introduced into the ecosystem a capacity to regulate local *Drivers* and *Pressures* which did not exist 40 years ago. The changes in human behavior have occurred in *Response* to the perception that *Pressures* have increased and to evidence of decline in conditions in the marine environment, such as water quality and the quality of coral reefs.

Protected Natural Areas

The designation of protected areas is one way of controlling *Pressures* caused by human activities in the ecosystem. Protected areas can be used to restrict a variety of different human activities.

Biscayne National Park

Biscayne National Park was established first as a national monument in 1968 and finally as a national park in 1980 to preserve Biscayne Bay and Elliot Key from development. The park encompasses most of central Biscayne Bay and the reef tract from Key Biscayne and Cutler Ridge, at its northern boundary, to Key Largo and Turkey Point at its southern boundary. The purpose of Biscayne National Park, as established by its originating legislation is:

> *To preserve and protect for the education, inspiration, recreation, and enjoyment of present and future generations a rare combination of terrestrial, marine, and amphibious life in a tropical setting of great natural beauty.*

Currently, the waters of the park are used extensively for recreation by residents and visitors to the Miami area. A new general management plan, expected to be finalized in 2013, proposes to establish marine protected areas within the park where boat access and fishing will be restricted.

National Wildlife Refuges

The Hobe Sound National Wildlife Refuge, in Martin County, consists of 1000 acres of land encompassing sea turtle nesting habitat, on Jupiter Island, and sand scrub community on the mainland. The refuge was established in 1969 for the purpose of preserving nature habitat and populations, the preservation of cultural resources, recreation, and education. The refuge preserves some of the last remaining pristine dune and pine scrub habitat in the region.

Florida State Parks

Florida's system of state parks was established in 1925 to preserve areas of natural beauty, historical sites, and memorials. Beginning in the 1970s, the emphasis shifted to implementing natural systems management aimed at restoring and maintaining natural biological communities and processes while also providing for public access and use of the parks. The SEFC region includes the following Florida state parks (Figure 11):

- Jonathan Dickinson State Park
- Seabranch Preserve State Park
- John D. MacAuthur Beach State Park
- John U. Lloyd Beach State Park
- Oleta River State Park
- Bill Baggs Cape Florida State Park
- Hugh Taylor Birch State Park

Florida State Aquatic Preserves

Florida's system of aquatic preserves was established in 1975 for the purpose to preserve the aesthetic, biological, and scientific values in the protected areas for the enjoyment of future generations. Some of the preserves along the southwest coast were established prior to this date. Aquatic preserves protect submerged lands that provide critical nursery and feeding habitat needed to support coastal fisheries and marine wading birds. Aquatic preserves also protect areas of cultural value, archaeological and historic sites, and provide opportunities for recreation, e.g., swimming, fishing, and boating. The SEFC region includes the following aquatic preserves (Figure 11):

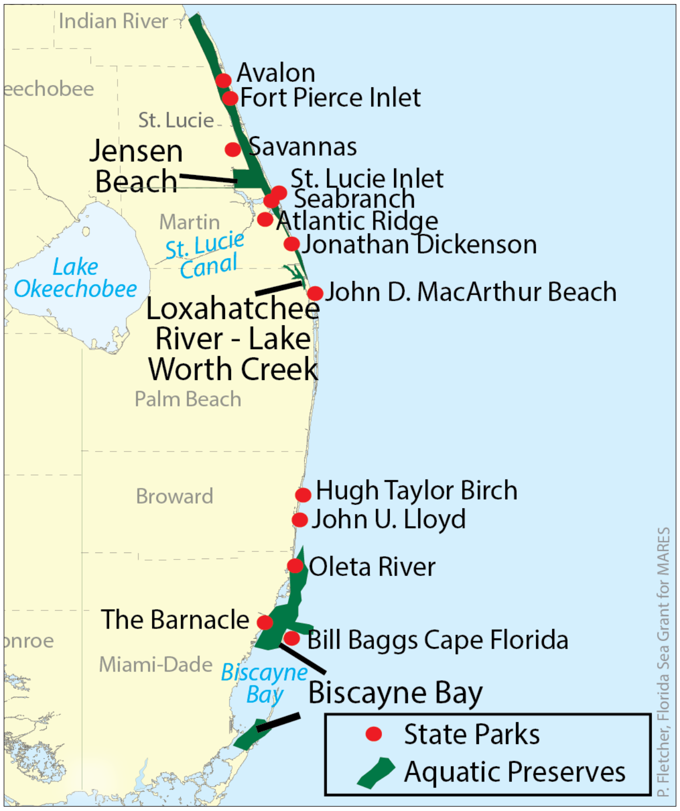
- Biscayne Bay
- Biscayne Bay–Cape Florida to Monroe County line
- Loxahatchee River–Lake Worth Creek
- Jensen Beach to Jupiter Inlet

In addition to the Florida state parks and aquatic preserves, the SEFC region also has a large number of county parks that protect natural areas of the coast.

Coastal Management

The Coral Reef Conservation Program (CRCP), administered by the Florida Department of Environmental Protection, coordinates activities among a large number of partners toward the goal of preserving and restoring the coral reefs along the southeast coast. The CRCP was created in 2004 to implement the local action strategy for the U.S. Coral Reef Task Force for protection of the reefs. Partners in this effort include local stakeholder groups and agencies of the county, state, and national governments. The local action strategies consist of research, monitoring, outreach, and education activities. In addition, the CRCP also has responsibility for responding to incidents, such as ship groundings, that physically damage the reef.

The Florida Fish and Wildlife Conservation Commission (FWC) is authorized by the Florida Constitution to enact rules and regulations regarding the state's fish and wildlife resources. Created in 1999, its goals are to manage fish and wildlife resources for their long-term well-being and the benefit of people (FWC, 2012a). Fishing regulations set in place by the FWC include size limits, the amount of fish one



P. Fletcher, Florida Sea Grant for MARES

Figure 11. Map depicting southeast Florida's state parks and aquatic preserves.

is allowed to catch (bag limits), closed seasons, and species which are prohibited to fish. With these measures, the FWC tries to manage the different fish species depending on their conservation needs (FWC, 2012b). Next to the harvest of fish, fishing gear can also have a negative impact on coral reef and hardbottom. To diminish the physical damage done to coral reef and hardbottom by lost traps, the FWC has two programs dedicated to removing lost and abandoned traps from state waters (FWC, 2012a).

Florida currently has implemented strong management controls on recreational and commercial fishing (FWC, 2012a; FWC, 2012b). One control mechanism that has been successful is the establishment of Marine Protected Areas and "no-take" sanctuaries (Lester *et al.,* 2009). A "no-take" region of the Merritt Island National Wildlife Refuge was established in 1962; in a recent study, samples from the no-take areas had significantly greater abundance and larger fishes than fished areas (Johnson *et al.,* 1999**)**. This concept has also been successfully applied in the Florida Keys (Toth *et al.,* 2010), and has been suggested for the southeast coast (SEFCRI, 2004). A survey published in 2001 (Johns *et al.,* 2001) indicated that a majority of residents of the three counties would support "no take" zones on 20-25 percent of the existing natural reefs.

Ecosystem Research and Monitoring

The Southeast Florida Coral Reef Initiative (SEFCRI) supports a team of marine resource professionals, scientists, and stakeholders from government agencies and other organizations who coordinate research and monitoring and develop strategies for protection and restoration of the reef. The work of SEFCRI supports CRCP and its partners in their management responsibilities. From its beginning in 2003, the activities of SEFCRI have been focused on four main areas of concern: land-based sources of pollution; impacts of the maritime industry and coastal construction; impact of fishing, diving, and others uses of the reef; and public education and awareness. In southeast Florida, water quality monitoring is limited to inland waters (Trnka *et al.,* 2006; Caccia and Boyer, 2005; Torres *et al.,* 2003; Carter, 2001). There are no long-term data available for ocean waters, but the Broward County Environmental Protection Department began a coastal water quality monitoring program in 2005 with nutrients, chlorophyll, salinity, dissolved oxygen, and pH measured at three sites in Port Everglades on a monthly basis (Craig, 2004; Banks *et al.,* 2008).

Hydrologic Restoration

Different agencies work together to implement more sustainable water management in southeast Florida. These agencies include the South Florida Water Management District (SFWMD) and its Water Resources Advisory Commission (WRAC). The SFWMD is a regional governmental agency in charge of the water resource. Created in 1949, the agency is responsible for managing and protecting the water resources of South Florida by balancing and improving water quality, flood control, natural systems, and water supply. Its goal is to manage stormwater flows to rivers and freshwater discharge to South Florida's estuaries in a way that preserves, protects, and, where possible, restores these essential resources (SFWMD, 2011a). The WRAC is an advisory body to the South Florida Water Management Governing Board and the South Florida Ecosystem Restoration Task Force. Its main purpose is to improve public participation and decision-making in water resource-related topics. For this reason, the members of the Commission come from the following different backgrounds: business, agricultural, environmental, tribal, governmental, and public interests (SFWMD, 2011c).

The SFWMD implements Florida state water policy through various programs. Ongoing programs that affect the SEFC coastal marine ecosystem include the following:

- The Biscayne Bay Surface Water Improvement and Management (SWIM) plan coordinates federal, state, and local government and the private sector in efforts to restore this damaged ecosystem, prevent pollution from runoff and other sources, and educate the public. In addition to addressing these issues, identified in 1988, the updated plan analyzes the extensive data collected since 1988 to document the effectiveness of the initial plan's strategies and identify new issues and solutions to problems facing Biscayne Bay and its watershed.

- Minimum flows and levels criteria have been established for the Northwest Fork of the Loxahatchee River and the St. Lucie estuary. Along with water reservations, the minimum flows and levels criteria guide regional water management practices to better protect fish and wildlife in these estuarine ecosystems from changes in salinity and other changes associated with the regulation of freshwater inflows.

- Biscayne Bay Coastal Wetlands Project is designed to replace lost overland freshwater inflow and groundwater inflow into central Biscayne Bay. The goal is to improve the ecological health of the bay, especially in its tidal creeks and nearshore habitat. The Biscayne Bay Coastal Wetlands project is a component of the regional CERP.

Southeast Florida Regional Climate Change Compact

Climate change threatens millions of people and businesses along the SEFC by shifting weather patterns, increased hurricane intensity, and rising seas (South Florida Regional Planning Council, 2008). For these reasons the South Florida Regional Planning Council wants to take actions against climate change. Between 1990 and 2005 greenhouse gas emissions increased in Florida by about 35 percent, and a business-as-usual projection to 2025 showed an increase in greenhouse gas emissions of 86 percent compared to the 1990 level (Strait *et al.,* 2008). On July 13, 2007, Governor Charlie Crist signed executive orders (07-126, 07-127, 07-128) which required South Florida to reduce its GHG emissions to 80 percent below the level of 1990 by 2050 (South Florida Regional Planning Council, 2008). Recent actions that Florida has undertaken, such as the electric utility cap and adoption of the California Clean Car Standards, will lower the increase of greenhouse gas emissions to 55 percent of the 1990 level by 2025 (Strait *et al.,* 2008).

In *Response* to the relatively new threat of climate change and accelerated sea-level rise, Miami-Dade, Broward, and Palm Beach counties joined with Monroe County in 2009 to form the Southeast Florida Regional Climate Change Compact. The Compact is developing a regional strategy to foster collaboration in southeast Florida on mitigating the causes and adapting to the consequences of climate change.

As a first step towards mitigating the effects of accelerated sea-level rise, as a consequence of climate change, the Compact has developed a consensus trajectory for sea level projected until 2060 (Figure 12) (Southeast Florida Regional Climate Change Compact Counties, 2011). The consensus projection is based on "(1) global and local sea level measurements which document an accelerating rate of sea-level rise, (2) the preponderance of scientific evidence that recent land-based ice loss is increasing, and (3) global climate models that conclude the rate of sea-level rise will continue to accelerate."

The projected trajectory is enveloped by an upper and lower rate projection, reflecting the underlying scientific uncertainties (Figure 12). Sea level in South Florida is projected to rise 1 foot above the 2010 reference level, relative to land surface, sometime between 2040 and 2070. A two-foot rise is considered possible by 2060. By 2060, it is expected that the rate of sea-level rise will have increased to between 2 and 6 inches per decade. For reference, between 1913 and 1919, sea level rose at an average rate of 0.88 inches per decade.

Response by Individuals

People change their use of the coastal marine environment for reasons that are unique to each individual. Factors that contribute to these decisions can be categorized as related to

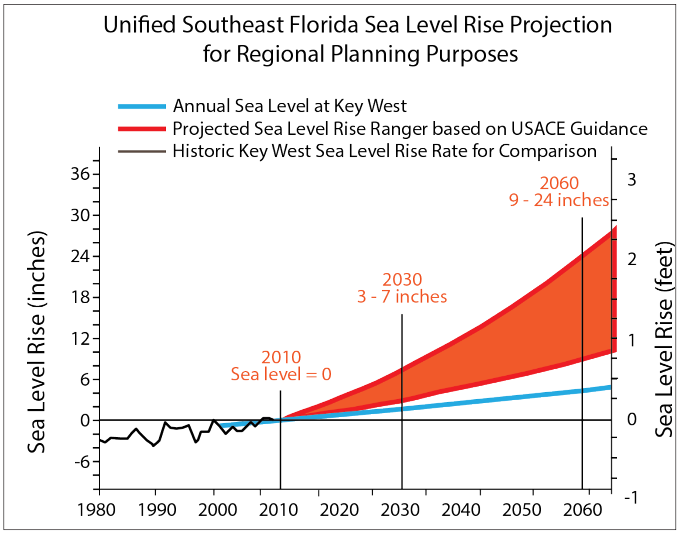


Figure 12. Unified southeast Florida sea-level rise projection for regional planning (Southeast Florida Regional Climate Change Compact, 2011; calculations courtesy of K. Esterson, U.S. Army Corps of Engineers).

their demand for services provided by the ecosystem or their level of satisfaction obtained while in the coastal marine environment. Changes in demand often can be understood as a response to economic conditions, such as costs and ability to pay, and regulations that restrict access and/or use of the environment. Satisfaction is typically viewed as one of the most important management goals when providing quality recreational opportunities.

Unfortunately, satisfaction is a difficult concept to measure. Simply asking an individual how satisfied they are does not inform a manager why they are or aren't satisfied or what contributed to their response. Other factors must be considered that include subjective personal and social aspects of a user's experience; these include conflict, crowding, expectations, normative standards, etc. While these other factors can be easily justified on their own (particularly for the commercial operators), they need to be considered when seeking to understand satisfaction.

The recreational user seeks satisfaction in the experience of obtaining a desired ecosystem service facilitated/delivered through resource management. The user's experience has two parts: the environmental and the social. The first, the environmental, is determined by the attributes typically thought of as being provided via a marine ecosystem; these are characterized by the "attributes that people care about." The second, the social, is determined by interactions with other people. These are related to the services that individuals often think of as services when participating in their activity. It should be noted that there are additional social "services" that should be considered for inclusion. These might include relaxation, solitude, education, family time, etc. These services are not based directly on the physical attributes, but rather the management goals in combination with the resource.

Crowding

Perceived crowding is a concept that is at best only weakly related to user density. Instead, it is related to factors such as goal interference, expectations and discrepancies, normative standards, etc. The "ecosystem service" being desired by users, and delivered through resource management, would be a mix of user types, user levels, and experiences consistent with what the combination of the resource and management goals are intended to provide.

For example, crowding may be a factor limiting recreational boating use in Broward County. Measured on a per capita basis, fewer residents of Broward County engage in recreational boating than in the rest of Florida. Broward County residents have higher-than average incomes and this, combined with residents' proximity to the coast, would argue for a higher demand for recreational boating. An explanation for this anomaly might be found on the supply side. People may be deterred from engaging in recreational boating activities by crowding or congestion at boat ramps, to get out onto the water, or at recreational resources such as artificial reefs or prime fishing locations (Johns *et al.,* 2001).

Conflict

Conflict is typically defined by the mixing of motorized and non-motorized users. The two typically don't mix. A second characteristic of conflict is that it is typically asymmetrical in that one group (fishermen, for example) will experience conflict while the other group (motor boaters or jet skis, for example) will not experience conflict. Conflict is related to perceived crowding, which is then related to satisfaction. Users desire the ecosystem service of limited user conflict.

Expectation

Humans do things in the expectation that certain outcomes (ecosystem services) will follow. Users in this case have certain expectations for certain ecosystem services. They might expect certain a number of fish to catch or a number of other divers to be in the water at the same time (not too many or too few), or a healthy and pristine ecosystem. This does not mean that user expectations should automatically be met. Expectations are often unrealistic or inappropriate for a given environmental condition or management mandate. Instead, expectations should be considered in the sense that they influence how users evaluate conflict, crowding, or satisfaction. Thus, expectations aren't a true ecosystem service but rather an intervening variable in understanding other ecosystem services.

Normative Standards

Normative standards are socially agreed upon standards of what should be. Users can generally agree on what constitutes an acceptable level of coral bleaching, or use levels, or coastal impacts due to human use, or management mandates for particular resource types or classifications. It is usually necessary and best to examine norms according to meaningful subgroups, since an overall average user really doesn't exist. Like expectations, norms are not ecosystem services. They are the standards against the extent to which ecosystem services are being delivered or met. They are a comparative device.

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Water Column

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In a nutshell:

- The diverse habitats and living marine resources within the southeast Florida marine ecosystem depend on low concentrations of nutrients and phytoplankton in the water column to exist and thrive.
- People value clear water for diving, fishing, good quality seafood, fisheries, and beaches untainted by toxins and pathogens.
- Small increases in nutrient concentrations lead to undesirable phytoplankton blooms and stimulate the overgrowth of macroalgae on the coral reef.
- Eutrophication caused by nutrients from either land-based sources in the region (coastal inlets, treated-wastewater effluent, groundwater discharge, urban runoff) or from far-field sources in the offshore (ocean upwelling, atmospheric deposition, advection of upstream water masses) poses a major threat to the water column.

The water column is defined by its physical, chemical, and biological characteristics and includes suspended benthic sediment, phytoplankton, and zooplankton. This encompasses all aspects of water quality, in addition to zooplankton and physical properties such as temperature, salinity, etc. (Figure 1). The water column does not include benthic organisms that are incorporated into the hardbottom and seagrass submodels or fauna incorporated into the fish and shellfish submodel. All other aspects of the ecosystem rely upon the biological, chemical, and physical habitat traits encompassed in the water column submodel.

The water column is bounded on the west by the highly developed southeast coast of Florida. The nearly linear north-south coastline consists of barrier islands, generally bound by barrier islands interrupted by inlets where inland waters flow into the coastal ocean on the ebb tide. The water column is heavily influenced by the north-flowing Florida Current to the east and, to a lesser extent, by a nearshore current which is variable in its direction and magnitude. The combination of the variable nearshore current and the strong Florida Current offshore produces a longitudinal gradient of current velocities across the region. The area is frequently exposed to hurricanes and winter storms.

Generally, conditions in the SEFC water column are oligotrophic, characterized by low nutrient concentrations with low concentrations of phytoplankton and organic matter, high water clarity, and high concentrations of dissolved oxygen. Depending on the prevailing oceanographic conditions and location, nutrient sources are dominated by near-field (e.g., inlets and outfalls, ground-water discharge) or far-field (e.g., Mississippi River and Southwest Florida Shelf runoff, atmospheric deposition, ocean upwelling) processes. If nutrient concentrations increase, it is likely that phytoplankton (Boyer *et al.,* 2009), benthic macroalgae (Duarte, 1995; Valiela *et al.,* 1997), and the frequency of algal blooms will increase (Brand and Compton, 2007).

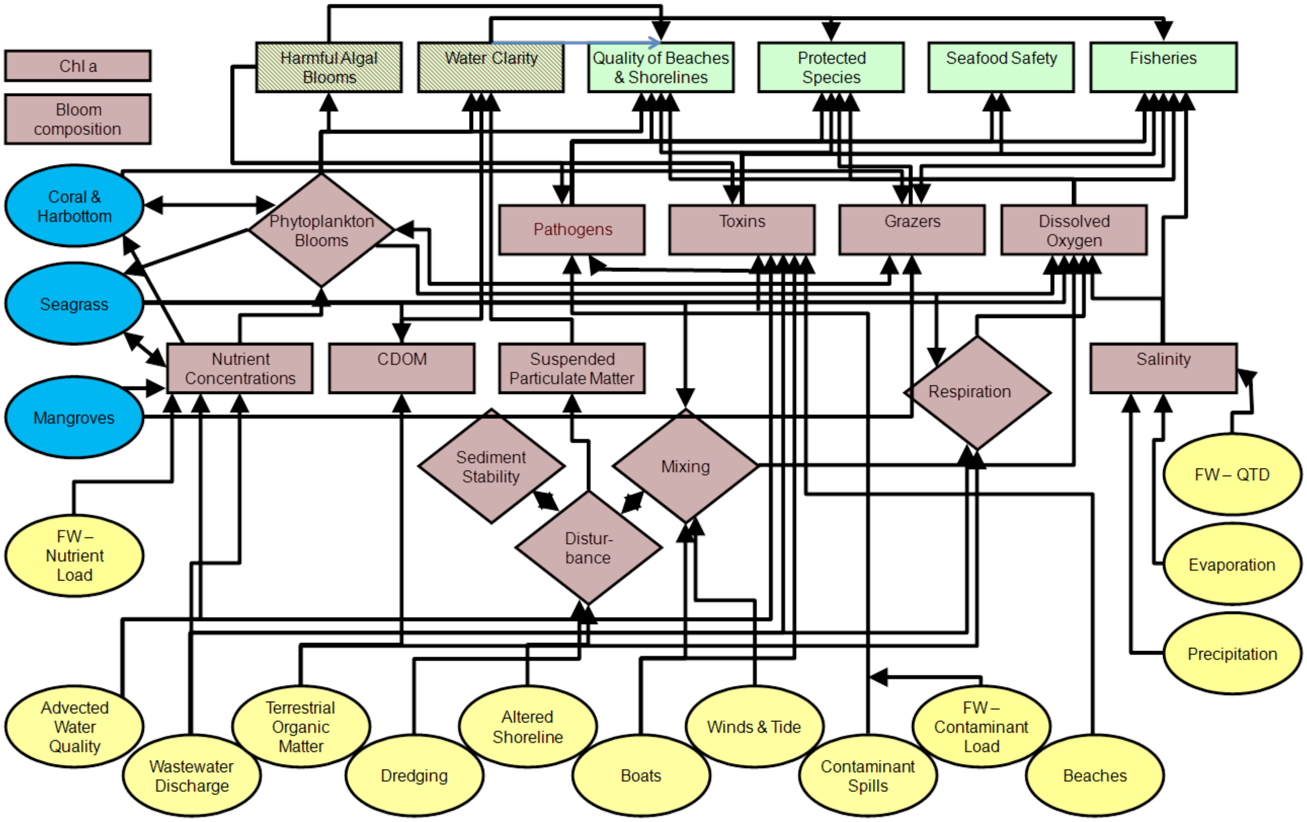

Figure 1. The water column conceptual ecological submodel for the southeast Florida coast.

Role in Ecosystem

The water column supports fisheries and their habitat. Conditions in the water column of the SEFC marine ecosystem must remain oligotrophic to sustain the key characteristics that distinguish this ecosystem and the *Ecosystem Services* derived from it.

Currently, the SEFC marine ecosystem is characterized by hardbottom surfaces and/or sand, interrupted by three intermittent reef tracks, with some isolated seagrass beds which provide vital habitat for many fishery species (Banks *et al.,* 2008). Benthic cover includes macroalgae, octocorals, sponges, and stony corals (Banks *et al.,* 2008). The primary threat to benthic habitats is eutrophication due to increased anthropogenic nutrient loading. This may result in overgrowth by less desirable macroalgae (Anderson *et al.,* 2002). Recent investigations in the lower Keys have described an increase in diversity and abundance of macroalgae, possibly as a result of anthropogenic nutrient loading (Lapointe *et al.,* 2004; Lapointe and Bedford, 2010). Banks *et al.* (2008) noted that southeast Florida has less macroalgal cover than is found in the Florida Keys.

Attributes People Care About

The SEFC water column supports attributes of the environment that people care about. These attributes are directly related to *Ecosystem Services* provided by the SEFC marine ecosystem:

- Harmful algal blooms
- Water clarity
- Quality of beaches and shoreline
- Protected species
- Seafood safety
- Fisheries

Harmful Algal Blooms

Harmful algal blooms (HABs) along the SEFC are primarily composed of the dinoflagellate, *Karenia brevis,* which contains a brevetoxin compound that can aerate and cause respiratory distress. HABs also causes paralytic shellfish poisoning via consumption of contaminated shellfish harvested from an area that has experienced a recent *K. brevis* bloom (Kirkpatrick *et al.,* 2004). Large blooms of *K. brevis* may result in hypoxic conditions (low dissolved oxygen) fatal to many species (Hu *et al.,* 2006). Blooms may be locally originating or may have originated on the west Florida coast and subsequently advected to southeast Florida via the Florida Current (Lapointe and Bedford, 2010; FWC, 2012a). Blooms of macroalgae, which can smother benthic habitats, are a related problem. The macroalgae in southeast Florida waters include *Dictyota ssp.* and *Halimeda ssp.* (Banks *et al.,* 2008).

Water Clarity

The diving and fishing industries rely upon good water clarity to ensure that business remains optimal. The clarity of the water is a direct product of light attenuation and is thus dependent upon the concentrations of chromophoric dissolved organic matter, phytoplankton, and suspended particulate matter. In addition to aesthetics, appropriate light levels are critical to the survival of seagrass and coral species (Boyer *et al.,* 2009).

Quality of Beaches and Shoreline

The quality of the beaches and shoreline of the SEFC is important to tourists and residents and is essential to a $1.2 billion tourist industry (Johns *et al.,* 2001). The quality of the shoreline, beaches, and water is measured in terms of aesthetics and the likelihood of contracting a health problem. Beach closures due to no-swim advisories have been a chronic problem, in part due to the persistence of *Enterococcus* cells in both dry and tidally-wetted beach sand (Fleshler, 2010; Abdelzaher *et al.,* 2010).

Protected Species

The SEFC is home to a number of protected and/or endangered species, including sea turtles (green, leatherback, Hawksbill, Kemp's ridley, and loggerhead) and corals (Elkhorn and staghorn). Threats to sea turtles include loss of nesting beaches, loss of food supply (e.g., coral reefs), and hunting (NOAA Fisheries, 2012).

Seafood Safety

Mercury and toxins are the primary threats to the safety of seafood harvested in the coastal waters of southeast Florida (FDOH, 2012). Mercury enters the coastal and marine waters from the Everglades, which has been noted as having the highest mercury levels in fish in Florida (Axelrad *et al.,* 2011). A study comparing seafood mercury in a variety of fish from the Indian River Lagoon and Florida Bay found most lagoon fish safe for consumption (Strom and Graves, 1995). Some species (i.e., sharks) are recommended to never be consumed (FDOH, 2012).

Fisheries

Fisheries, both commercial and recreational, contribute a large percent of both dollars and jobs to the South Florida economy (Johns *et al.,* 2001; Fedler, 2009). Commercial fishing harvests include spiny lobsters, amberjacks, yellowtail, black grouper, and mutton snapper, although a 1998-2002 survey saw few or no groupers and snappers above legal minimum size off of Broward County (Fleur *et al.,* 2005; Gibson *et al.,* 2008). These fisheries species derive their energy directly or indirectly from primary producers, many of which are the phytoplankton located within the water column. Thus, productive fisheries require a healthy ecosystem with sufficient primary productivity and a balance of prey and predator species.

Quantifiable Attributes

The following key characteristics are or should be measured to assess the status of the SEFC water column:

- Nutrients
- Chromophoric dissolved organic matter
- Suspended particulate matter
- Phytoplankton blooms (algae species and biomass or concentration or chlorophyll as a surrogate)
- Food web changes
- Ocean currents

Several monitoring programs of varying scope are being conducted to assess conditions in the water column of the SEFC environment. While these monitoring programs are valuable, there is general agreement that a more comprehensive monitoring program is essential for the assessment and management of a healthy and productive ecosystem that can respond appropriately to the needs of the large population that it serves (e.g., CRCP, 2009).

The longest data base on SEFC coral reef health is the Southeast Florida Coral Reef Evaluation and Monitoring Program (SECREMP; www.nova.edu/ocean/ncri/research/southeast-florida-coral-reef-evaluation-monitoring.html). This program is designed to assess long-term trends of water quality and potential eutrophication in southeast Florida through the systematic measurement of water column parameters. The SECREMP program is organized by the Southeast Florida Coral Reef Initiative (SEFCRI; www.aoml.noaa.gov/themes/CoastalRegional/projects/FACE/faceweb.htm) and conducted by the National Coral Reef Institute of Nova Southeastern University. This project has recently increased the number of monitored reef sites to 17, ranging from Miami-Dade to Martin County, Florida, for benthic species cover and temperature (Gilliam, 2012). Monitoring includes occurrences of phytoplankton blooms and macroalgae percent cover.

The Florida Area Coastal Environment (FACE; www.aoml.noaa.gov/themes/CoastalRegional/projects/FACE/faceweb.htm) program of NOAA's Atlantic Oceanographic and Meteorological Laboratory is designed to examine water quality charac-teristics, particularly around the known point sources of anthropogenic materials, treated-wastewater outfalls, and coastal inlets.

The state of coral reefs and the general benthic environment are monitored by a number of groups including both professional and volunteer (diver) organizations (see Collier *et al.,* 2008 for a listing). The Harbor Branch Oceanographic Institute (a part of Florida Atlantic University) has hosted the Harmful Algal Blooms project since 1983 (www.fau.edu/hboi/OceanHealth/OHalgalblooms.php). A review of Florida's monitoring efforts, management recommendations, high risk areas, medical issues, and a literature review can be found at Abbott *et al.* (2009).

Nutrients

The term "nutrients" refers to biologically available species of nitrogen, phosphorus, and silicon, e.g., nitrite (NO_2^{-1}), nitrate (NO_3^{-1}), orthophosphate (PO_4^{-3}), and silicate (SiO_4^{-4}) (EPA, 2001). The SEFC waters, while stressed by the very high urban population, are low in nutrients, i.e., "oligotrophic," and provide a sustaining environment for corals, fish, and other flora and fauna (Banks *et al.,* 2008; Collier *et al.,* 2008). Sources of nutrients into the coastal ocean include treated-wastewater outfalls, inlets, city runoff, groundwater discharge, atmospheric deposition, and ocean upwelling (Collier *et al.,* 2008).

Chromophoric Dissolved Organic Matter

Light is fundamental to the health of SEFC ecosystems: corals, phytoplankton, and seagrasses need light for photosynthesis (Yentsch *et al.,* 2002; Kelble *et al.,* 2005). Light in the sea is affected by absorption, scatter, and refraction (Johnsen and Sosik, 2004). The most relevant measurement of light with respect to healthy ecosystems is that of photosynthetically available radiation, a measure of the spectral range of light used in photosynthesis, roughly 400-700 nm (GLOBEC, 2007). Absorption is chiefly the result of chromophoric dissolved organic matter (CDOM); scatter is a result of suspended particulates. CDOM is primarily derived from the decomposition of organic material such as seagrass, phytoplankton, and mangroves (Stabenau *et al.,* 2004; Romera-Castillo *et al.,* 2010; Shank *et al.,* 2010). CDOM has the important function of shading the benthic ecosystem from harmful ultraviolet rays

(Zepp *et al.,* 2007). However, excessive shading can limit photosynthesis (Kelble *et al.,* 2005).

Suspended Particulate Matter

Suspended particulates in the water attenuate light by absorption and scatter. In Florida Bay, particulates were found to be the dominant effect on light attenuation (Kelble *et al.,* 2005). A particular concern along the SEFC is the effect of anthropogenic activities on suspended solids, especially through activities like pipeline construction, installation of fiber optic cables, beach renourishment, and channel dredging (e.g., Volety and Encomio, 2006; Puglise and Kelty, 2007). Particle resuspension by wind can also be a significant factor (Liu and Huang, 2009).

Phytoplankton Blooms

NOAA maintains a HAB early detection and forecasting website (tidesandcurrents.noaa.gov/hab/#swfl) that records and archives occurrences of HABs in southwest, northwest, and eastern Florida, as well as Texas. A review of Florida's HAB monitoring efforts, management recommendations, high risk areas, medical issues, and a literature review can be found in Abbott *et al.* (2009).

Ocean Currents

The need for long-term monitoring of ocean currents and chemistry is widely recognized (e.g., Trnka *et al.,* 2006). Ocean currents in SEFC nearshore waters have been measured intermittently for decades, but few long-term, sustained data sets exist (e.g., Lee and McGuire, 1972; Düing, 1975). Surface currents have been measured by the WERA (WavE RAdar) system off of Miami-Dade County (http://secoora.org/data/recent_observation_maps/HFRadar/Miami_WERA), and a second system has been established east of Port Everglades (http://snmrec.fau.edu/sites/default/files/CODAR_Sites_Web.pdf) (Shay *et al.,* 2007). Periodic measurements of current profiles are conducted by water utilities near the offshore outfalls that discharge treated wastewater and as part of the FACE monitoring program (Carsey *et al.,* 2011).

Drivers of Change in the SEFC Water Column

Changes to the SEFC water column stem from both near-field and far-field drivers, and these can be both natural and anthropogenic in nature. The major anthropogenic driver is population density. The combined population of the three counties along the southeast coast (Miami-Dade, Broward, and Palm Beach) was recently measured at over 5.5 million people, and this number is projected to increase by nearly a half million per decade (FOEDR, 2012). The human population creates a demand for food, water, shelter, recreation, and economic growth. Meeting these demands results in significant pressures on the SEFC coastal marine ecosystem.

Fishing and Diving

Fishing and diving are vital recreational activities with important economic consequences. Johns *et al* (2001) reported more than 11 million "person-days" at natural and artificial reefs in Miami-Dade, Broward, and Palm Beach counties during 2000, resulting in the employment of over six thousand people and an economic contribution of approximately $740 million. With respect to the ecosystem, however, fishing activities systematically remove large-bodied top predators from the ecosystem, drastically altering the food web (Jackson, 2001; Myers and Worm, 2003; Estes *et al.,* 2011). The food web is the array of feeding patterns by which energy and nutrients are transferred from one species to another. At the base of the food web are primary producers, marine plants (phytoplankton, i.e., microalgae), and benthic vegetation (seagrasses and macroalgae) that employ energy from the sun and available nutrients to grow. The primary producers provide food for grazing species such as zooplankton and small fish and shellfish and for filter feeders such as sponges. These altered food webs can have downward cascades that have been observed to alter zooplankton concentrations and thus are likely to alter grazing upon phytoplankton (Shackell *et al.,* 2010).

Water Management

The presence of nearly six million people living along the SEFC has necessitated potable water production and distribution systems. Potable water needs in Miami-Dade, Broward, and southeastern Palm Beach counties are primarily met by withdrawing water from the surficial Biscayne Aquifer, whose waters are derived from local rainfall and, during dry periods, from canals ultimately linked to Lake Okeechobee (Carriker, 2008). Desalination is used on the west coast (Cooley *et al.,* 2006) and has been considered for southeast Florida (Race, 2006); the process is expensive and creates brine that must be discharged into coastal waters (FDEP, 2010a). Agricultural water needs and flood control issues, as well as groundwater control (e.g., saltwater intrusion, phosphorus reduction), are managed through the operation of an extensive canal system that collects and channels freshwater to the coast (SFWMD, 2010). In addition, an Intracoastal Waterway extends 374 miles along the SEFC, from Fernandina Harbor to Miami Harbor (Florida Inland Navigation District, 2000).

Discharge of surface waters flowing into the ocean from northern Miami-Dade, Broward, and Palm Beach counties is predominantly channeled through a series of inlets: Norris Cut, Bear Cut, Government Cut, Haulover Inlet, Port Everglades Inlet, Hillsboro Inlet, Boca Raton Inlet, Boynton Inlet, and Palm Beach (North Lake Worth) Inlet. These inlets must be considered major sources of land-based pollution. The U.S. Geological Survey, in a 1998 study of water quality in South Florida, listed domestic wastewater facility discharges (1500 facilities), industrial wastewater discharges (including leachage and runoff from contaminated land), septic tank discharges (nearly a half-million), agricultural wastewater runoff (citrus farming, dairy and beef operations), runoff from landfills (40 active landfills), and urban wastewater (stormwater) runoff as the leading categories of land-based pollution (Marella, 1998). Anthropogenic materials from inlets have been implicated in bloom activity on coral reefs (Lapointe and Bedford, 2010).

Ocean outfalls for the disposal of treated-wastewater are noted point sources of anthropogenic materials (EPA, 1992). There are five treated-wastewater outfalls continuously operating in southeast Florida; their combined flow in 2011 was 199 million gallons per day (Carsey *et al.,* 2013). The number of ocean outfalls has decreased significantly over the years; there were ten operating in 1972 (Lee and McGuire, 1972). Current legislation (Florida Statute 403.086; www.flsenate.gov/Laws/Statutes/2011/403.08601) requires termination of ocean outfalls for routine effluent discharge by 2025 and requires that a majority of the wastewater previously discharged be beneficially reused (FDEP, 2010b). This, however, presents a significant challenge to municipalities who must design, finance, and implement these alternative systems (e.g., Figueroa, 2008). One treated-wastewater ocean outfall (Boynton Beach) has already ceased operation, except under storm conditions (FDEP, 2010b). Raw sewage that had formerly been discharged into the surface waters of Florida by small wastewater treatment plants has been significantly reduced by application of the National Pollution Discharge Elimination System (NPDES), a federal program to reduce pollution from point sources (Waddell *et al.,* 2005).

Another important delivery of freshwater to the coastal ocean occurs through submarine groundwater discharge (SGD), which is now recognized as a major vector of anthropogenic materials and thus an area of growing interest and concern (Finkl and Charliert, 2003; Paytan *et al.,* 2006). SGD transports nutrients introduced into the environment from activities such as wastewater disposal from septic systems and the agricultural and urban use of fertilizers (Howarth *et al.,* 2003; Lapointe *et al.,* 1990). It has been estimated that nitrates from SGD sources in west-central Florida may exceed that of rivers and atmospheric deposition (Hu *et al.,* 2006). Finkl and Krupa (2003) estimated that ground fluxes of nutrients to Palm Beach County averaged 15,690 kgN/d and 1134 kgP/d, more than double that of surface water fluxes (6775 kgN/d and 540 kgP/d).

Climate Change

Global emissions of greenhouse gases such as carbon dioxide (CO_2) produce a two-fold stress on the SEFC coastal marine ecosystem. First, rising CO_2 concentrations in the atmosphere and ocean surface waters cause a decrease in the aragonite saturation state of seawater and lowers the pH; this phenomenon is commonly referred to as ocean acidification (Feely *et al.,* 2009). This decrease in pH can have detrimental effects on calcifying organisms including coral reefs (Manzello *et al.,* 2008; Kleypas *et al.,* 2006). However, the exact magnitude and direction of this effect on different components of the ecosystem is unclear given the variety of responses between different organisms and the gradual nature of acidification which, occurring over several generations, allows populations of some organisms to adapt (Hendriks *et al.,* 2010).

Secondly, according to the IPCC (2007) report, the increase in CO_2 is resulting in warmer ocean temperatures and changes in rainfall patterns. These changes to rainfall and temperature will change the species of animals and plants in the water column (e.g., Caron and Hutchins, 2012; Paerl and Paul, 2012; Karl *et al.,* 2009). The warmer oceans will also lead to sea-level rise; generally accepted models suggest 23-61 cm by 2060 (USACE, 2011). Many authors consider these predictions to be conservative (e.g., Wanless, 2011; Obeysekera *et al.,* 2011). Higher sea levels will increase coastal inundation, especially during extreme events such as "king tides" and storm surges (Florida Oceans and Coastal Council, 2010; Zhang, 2011). In addition, storm surges would force large quantities of material, including sediments, sewage, and city runoff, into the nearshore water column following inundation (Dubois, 1990; Berry *et al.,* 2012; Flynn *et al.,* 1984; Hu *et al.,* 2004; Parker *et al.,* 2010).

Mechanisms of Change

The primary mechanisms by which these *Drivers* bring about change in the SEFC water column is through phytoplankton blooms, a loss of grazers in the food web due to overfishing, disease, and other physiological effects on organisms.

Phytoplankton Blooms

Phytoplankton blooms of both native and non-native species in SEFC waters have been noted for decades. In 1994-1995, blooms of *Codium isthmocladum* were recorded in reefs off of Broward and Palm Beach counties (Lapointe *et al.,* 2005a). Blooms of *Caulerpa brachypus* var. *parvifolia* occurred in 2001 (Lapointe *et al.*, 2005b), and *Lyngbya spp.* blooms were observed off of Broward county in 2003 (Paul *et al.,* 2005). In the spring of 2007, blooms of *Cladophora liniformis, Enteromorpha prolifera,* and *Centroceras clavulatum* were observed (Banks *et al.,* 2008). Abbott *et al.* (2009) found more than 50 harmful alga in Florida marine waters, producing a variety of toxins including saxitoxins (from puffer fish), brevetoxins (from *K. brevis*), and ciguatoxins (from the benthic dinoflagellate *Gambierdiscus toxicus*). Brevetoxins affect humans both through the eating of shellfish (neuotoxic shellfish poisoning) and through the inhalation of marine aerosols containing the toxin (Fleming *et al.,* 2005).

A bloom occurs when an alga species rapidly increases in number to the extent that it dominates the local planktonic or benthic community (Valiela *et al.,* 1997; Kirkpatrick *et al.,* 2004). HABs are phytoplankton blooms that can cause human, fish, or manatee poisoning, economic loses, and disruptions to the ecosystem (Fleming *et al.,* 2011; Smayda, 1997). When the bloom organisms die and decompose, they may consume so much oxygen that other species may not be able to survive (anoxia) (Abbott *et al.,* 2009). In southeast Florida, some HABs are naturally-occurring events caused by species of algae native to the region (Abbott *et al.,* 2009). Other HAB events concern non-native algal species (Collier *et al.,* 2008).

The increase in phytoplankton blooms likely poses the most immediate and severe threat to the SEFC water column. In recent years, debate has intensified as to whether anthropogenic activities are increasing bloom frequency and duration; a recent metadata review suggests that increases in HABs along the southwest Florida coast were related to increased nutrient availability (Brand and Compton, 2007). Although phytoplankton blooms are a natural phenomenon, increased nutrient loading from point and non-point pollution sources can increase their frequency, magnitude, duration, and spatial extent. This, in turn, can potentially damage the ecosystem and reduce the quantity and quality of ecosystem services.

Food Web Alterations

In southeast Florida, the food web has changed significantly in recent times. The numbers of large animals at the top of the food web, like fish of the snapper-grouper complex, manatees, sawfish, large sharks, and sea turtles, have been reduced drastically relative to historic levels, in large part due to historical exploitation and present-day overfishing (Al-Abdulrazzak, 2012; Ault, 2012). Another type of perturbation of the food web is from algal blooms. Removing the largest of marine predators causes food web changes that can ultimately decrease grazing upon phytoplankton and macroalgae (Shackell *et al.,* 2010). By decreasing grazing upon phytoplankton, blooms of phytoplankton can become more intense without an increase in nutrient loading. The loss of grazers, specifically benthic sponges, has been implicated as a major contributor to phytoplankton blooms in north-central Florida Bay (Peterson *et al.,* 2006).

Blooms of macroalgae can be caused by removal of macroalgal grazers from the food web in addition to the effect of increased nutrient availability, i.e., "top down" versus "bottom up" control (Valiela *et al.,* 1997). Macroalgal blooms are usually associated with non-indigenous species such as *Lyngbya*, *Caulerpa,* and *Codium ssp.* (Collier *et al.,* 2008). These blooms are not harmful through chemical toxicity but through disturbance to the ecosystem, e.g., crowding out other species (Collier *et al.,* 2008).

Florida currently has implemented strong management controls on recreational (FWC, 2012b) and commercial fishing (FWC, 2012c). One control mechanism that has been successful but is not yet in place along the SEFC is the establishment of Marine Protected Areas (MPA) and "no-take" sanctuaries (Lester *et al.,* 2009). A "no-take" region in the Merritt Island National Wildlife Refuge, near Cape Canaveral, was established in 1962; samples from the no-take areas had significantly greater abundance and larger fish than fished areas (Johnson *et al.,* 1999). The Tortugas Ecological Reserve, comprised of two separate areas near the Dry Tortugas National Park, was established as a no-take reserve in 2001, and a recent report noted increases in biomass of previously exploited species and significantly greater abundances and sizes of several key fish species (Jeffrey *et al.,* 2012). This concept has also been successfully applied in the Florida Keys (Toth *et al.,* 2010) and has been suggested for the SEFC (SEFCRI, 2004). A survey published in 2001 indicated that a majority of the residents in Miami-Dade, Broward, and Palm Beach counties would support "no take" zones on 20-25 percent of the existing natural reefs (Johns *et al.,* 2001).

Disease

Disease to both humans and marine life as a result of increased pathogen and toxin concentrations in the water column, or even the perception that disease was more prevalent in the water column, would impact *Ecosystem Services* such as swimming, diving, and the consumption of its marine life (Abdelzaher *et al.,* 2010).

Physiology

Changes in the salinity, temperature, and aragonite saturation state of the SEFC water column affects the health of marine organisms by changing the efficiency of their physiological processes. The impact of ocean acidification on marine organisms is highly variable, although it appears unlikely that effects will be dramatic in the short term (Hendriks *et al.,* 2010). However, changes due to temperature increases could be more pronounced because many marine organisms in southeast Florida are already living near their thermal maximums (Manzello *et al.,* 2007).

Topics of Scientific Debate and Uncertainty

Nutrient and toxin loading into the coastal ocean has not been adequately quantified. Of the recognized sources (treated-wastewater outfalls, ocean inlets, city runoff, groundwater discharge, atmospheric deposition, and ocean upwelling), accurate loading data are only available for the first source, i.e., treated-wastewater outfalls.

Understanding how altered nutrient and toxin loading affects water quality and, thus, habitats, is a primary research need. Most of the sources are anthropogenic; understanding the impact of human development on the SEFC marine ecosystem needs to be quantified. Several long-term programs are addressing this need, but the challenges are daunting (CRCP, 2009; Trnka *et al.,* 2006).

Each square mile of pristine coastline replaced with impermeable, developed land has negative impacts on water quality, and there is a need to better quantify these impacts for use in management strategy evaluations. Understanding these relationships improves modeling accuracy and thus increases our ability to evaluate management plans accurately prior to their adoption.

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Fish and Shellfish

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In a nutshell

- Fish and shellfish contribute to a productive coastal marine ecosystem that supports commercial and recreational fisheries both inshore and on the coral reef extending along the southeast Florida coast.
- A significant portion of the southeast Florida regional economy is supported by people from throughout the U.S. and abroad who are attracted to world-class recreational fishing opportunities and the spectacular diversity of marine species they can view through diving and other activities.
- The development of a high-density urban area has reduced critical inshore nursery habitats, and fish populations in the coral reef ecosystem show the effects of unsustainable overfishing.
- Fish and shellfish populations are vulnerable to continuing impacts from overfishing, water management, shoreline modification, and coastal construction, which will be increasingly driven by responses to sea-level rise.

Definition of the Resources

The reef fauna of the SEFC are similar to those found on the coral reef of the Florida Keys and elsewhere in the Caribbean region. The great diversity of marine species contributes to the designation of Florida as the "fishing capital of the world" (FWC, 2003). The coastal marine ecosystem of the SEFC supports both commercial and recreational fisheries and related tourism activities, and these are an important component of the regional economy (Ault *et al.,* 2005a). The coastal marine ecosystem of the Florida Keys and Dry Tortugas lies within the West Indian zoogeographic area, a subregion of the Neotropical Province. This area includes the Bahamas, Greater and Lesser Antilles, the northern coast of South America, the eastern coast of Central America, and South Florida. The lack of land barriers, connectivity of water masses, and ocean currents facilitate larval transport of progeny among these areas.

This appendix focuses on a relatively few taxa chosen to represent different roles in the ecosystem. The coral reef complex includes 19 species of fish, the spiny lobster, and pink shrimp (Table 1). Ault and Franklin (2011) used these species to investigate the current status and trends for fish and shellfish on the reef tract. In addition, we review information on the status and trends of juvenile fish, Caribbean spiny lobster, and pink shrimp in Biscayne Bay. These species have

Table 1. Species of the SEFC coral reef ecosystem.

- Coral Reef Fisheries Complex:
    - -Greater amberjack
    - -Black grouper
    - -Blue angelfish
    - -French angelfish
    - -Gray angelfish
    - -Gray triggerfish
    - -Great barracuda
    - -Hogfish
    - -Mangrove (gray) snapper
    - -Mutton snapper
    - -Parrotfish
    - -Queen angelfish
    - -Red grouper
    - -Rock beauty
    - -Tomtate
    - -White grunt
    - -Yellowtail snapper
    - -Bonefish
    - -Atlantic tarpon
- Spiny lobster
- Pink shrimp
- Lionfish

been proposed as indicators for the condition of nearshore faunal communities that will be affected by hydrologic restoration of the Everglades (RECOVER, 2010). We also review information on the lionfish, an invasive marine fish currently becoming established in the region.

The species diversity and number of fish comprising the reef fish community vary between shallow inshore and deeper offshore locations. Inshore, hardbottom substrate, seagrass beds, other submerged aquatic vegetation, and the mangrove shoreline serve as nursery habitat for juveniles of many reef fish and other sport fish species (Browder *et al.,* 2005; Crigger *et al.,* 2005; Sime, 2005; Ault, 2008). These are ephemeral habitats affected by variations in freshwater inflow and erosion and redistribution of bed material by storm events and as a consequence of marine construction activities, such as beach renourishment (Banks *et al.,* 2008). Offshore, the reef habit supports a greater variety of species and higher densities of fish. Adult reef fish are caught for food and sport both inshore and on the reef. Commercial and sport fisheries also target spiny lobster and marine aquarium fish at both inshore and offshore locations, while pink shrimp, blue crab, and spotted seatrout are inshore catches. Other species of interest include tarpon and bonefish, both highly prized by the recreational fishery, and menhaden, mullet, and stone crab, targeted by the commercial fishery.

The pink shrimp supports commercial fisheries in Biscayne Bay and is a principal prey of sport fish and other predators in the southeast Florida region (Berkeley, 1984; Ault *et al.,* 1999; Johnson *et al.,* 2012). Pink shrimp spawn offshore and enter estuaries to spend their juvenile lives, growing rapidly to late juveniles and young adults and then returning to offshore spawning areas and fishing grounds. Pink shrimp is the documented prey of gray snapper, spotted seatrout, and a host of other sport fishes (Hettler, 1989; Ault, 2008). The generally high productivity of estuaries attracts predators. Predator abundance in estuaries is counterbalanced by high primary productivity that promotes fast growth and complex habitat structure that provides protection.

Larvae of the Caribbean spiny lobster are dispersed widely by ocean currents, and individuals found in the waters of the Florida Keys may have originated from nearly anywhere in the Caribbean and Gulf of Mexico. Post-larvae settle in shallow, protected waters where seagrass beds and mangrove-protected shorelines provide nursery habitat. Between the juvenile and adult stages, individuals migrate from these shallows into deeper waters of the coral reef and hardbottom habitats. They seek refugia within the three-dimensional structure of the coral reef, under sponges, or any other available cover in the hardbottom habitat. The Caribbean spiny lobster preys on snails, crabs, and clams, and it is preyed upon by many high-trophic level fish species.

Attributes People Care About

People care about sustaining the reef fish community and marine sport fisheries along the SEFC, as well as having a local source of fresh seafood. Reef fish support both a commercial and a recreational fishery and associated tourism activities such as SCUBA diving and snorkeling that account for a significant portion of the regional economy. The sustainability of the reef fish community depends on maintaining both offshore reef habitat consisting of coral and hardbottom communities and associated water column and the inshore habitats that support many reef species in their post larval and juvenile stages. Sustainability refers to the ability of a fish population to produce goods and services (i.e., landings) at sustainable levels in the short term, while maintaining sufficient reproductive capacity to continue providing these goods and services indefinitely into the future (Walters and Martell, 2004, Ault *et al.,* 2008).

Attributes We Can Measure

Ault and Franklin (2011) reviewed available fisheries-dependent data on the species of the coral reef complex. These data included information on the level of fishing effort, catch amount, and size of the fish caught, by species. The available data are not sufficient for a complete evaluation of the sustainability of the reef populations. However, the data do allow comparisons against sustainability benchmarks established by Florida state and U.S. federal fisheries agencies.

Two fishery-dependent data sources are related to the recreational fishery: the Marine Recreational Fishing Statistical Survey (MRFSS) and the National Marine Fisheries Service (NMFS) headboat fishery survey. The MRFSS collects data on recreational landings from shore-based fishing and from private vessels and charter boats. MRFSS estimates the catch, landings, and the combined total of releases and discards based on phone interviews and creel surveys. Fishing effort is the estimated number of fishing trips taken by individual anglers. The NMFS headboat survey collects fisheries and biological data from fishing vessels that carry multiple anglers who have paid “by the head.” The data include landings, by species, and “angler days,” a measure of fishing effort.

The Accumulated Landings System (ALS) provides data related to the commercial fishery, consisting of the quantity and value of marine species caught by fishermen and sold to established seafood dealers or brokers. Other catch and trip information are included. The ALS consists of data collected by the Florida Trip Ticket Program and the NMFS Trip Interview Program (TIP). In addition to quantity and value, the Trip Ticket program provides information on gear used and area fished, by trip. TIP is a shore-based sampling program in which port agents collect size and frequency data and age at length data from the catch as it is unloaded or while it is in storage at the fish houses. Port agents also collect data on the fishing trip, such as area fished, type and quantity of gear, fishing time, etc.

Several fishery-independent multispecies monitoring efforts collect data on fish (both juveniles and adults) and invertebrates in the reef ecosystem (Smith *et al.,* 2011) and on pink shrimp, blue crabs, other invertebrates, and small fishes in nearshore areas within Biscayne Bay (RECOVER, 2010). These are part of the monitoring and assessment plan established to characterize the response of the coastal ecosystem to changes in freshwater inflows anticipated as a result of hydrologic restoration in the Everglades. A visual survey of the fish community of the mangrove shoreline has been conducted twice each year since 1998. The data collected by this survey are analyzed to provide community statistics, such as taxonomic richness and species dominance, and abundance metrics for individual taxa, such as occurrence and density.

A complementary program samples small fish and invertebrates (reef fish prey) in the seagrass beds adjacent to the shoreline. The twice-year visual survey and alongshore epifauna sampling, along with bottom vegetation and continuously recorded salinity monitoring, are part of the Integrated Biscayne Bay Ecological Assessment and Monitoring (IBBEAM) project. From 2005-2011, another monitoring and assessment project, the Seagrass Fish and Invertebrate Network (FIAN), sampled fish, crabs, and shrimp living in seagrass beds at seven Biscayne Bay locations (North Miami, Port of Miami, north of Black Point, south of Black Point, Card Sound, Barnes Sound, and Manatee Bay) to characterize changes in the seagrass-associated community over time. In FIAN, data collected twice annually included abundance (individuals per square meter) by species, physical characteristics of the seagrass bed, and conditions in the water column at the time of sampling (salinity, temperature, turbidity, and water depth).

A general indication of the condition of fish populations and fisheries can be inferred from trends in fishery-related data, such as population density, catch, effort, catch per unit of effort, etc. U.S. fisheries assessment scientists compare current fishery data to standard benchmarks such as Maximum Sustainable Yield (MSY) and Spawning Potential Ratio (SPR) that they have computed from historic data to assess the condition of the stock. They also refer to other, more exacting indicators of sustainability. Ault and Franklin (2011) used a length-structured population model to estimate mortality rates and other population-dynamic parameters based on the mean size of animals obtained from the TIP data. This length-based assessment methodology has also been applied to the Florida Keys and Puerto Rico reef fish populations (Ault *et al.,* 1998, 2005a, 2005b, 2008).

Drivers of Change

Fish and shellfish in the SEFC marine ecosystem are threatened by (1) fishing, (2) alterations to inshore habitats (e.g., loss of mangroves, seagrasses, and intertidal zones to shoreline development, channel dredging, ship groundings, beach renourishment, etc.), (3) non-native species, and (4) disease (Figure 1). Human use of the SEFC marine environment is increasing in intensity as a direct consequence of the proximity of coastal marine ecosystems to the highly urbanized coastal areas that extend from Miami to West Palm Beach. For example, the number of vessel registrations in the SEFC region has increased steadily over the past 45 years from fewer than 40,000 in the mid-1960s to over 150,000 vessels in 2010 (Smith *et al.,* 2011). This growth reflects increasing recreational use of the coast, as commercial vessel registrations remained stable over this period while the number of recreational vessels tripled (Ault and Franklin, 2011).

Fishing

Intensive exploitation and overfishing are perhaps the major threats to the reef fisheries of southeast Florida (Ault *et al.,* 2005a, 2009). Generally, fishing can reduce ecosystem integrity in at least three ways. First, removing targeted species and killing non-target species (as bycatch) may result in cascading ecological effects (Frank *et al.,* 2005). Second, because fishing is size-selective, concerns exist about ecosystem disruption by removal of ecologically-important species such as top-level predators (e.g., groupers, snappers, sharks, jacks) and prey (e.g., shrimp, baitfish) of certain

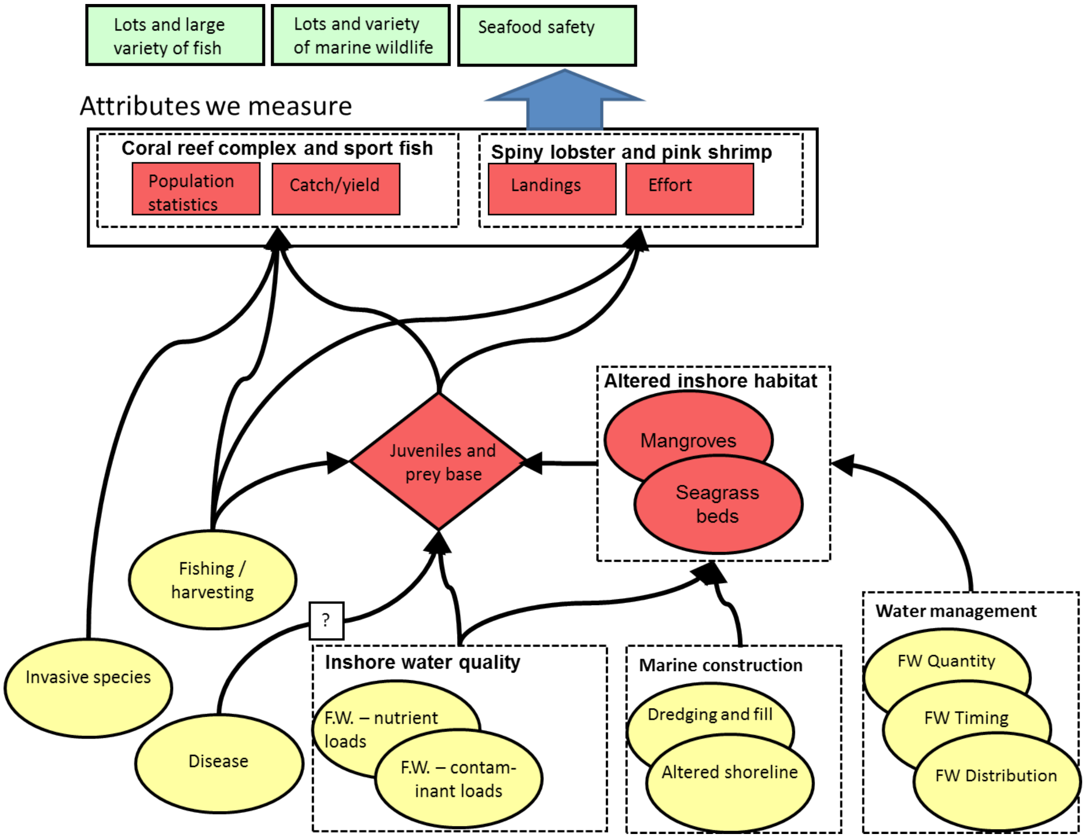

Figure 1. The fish and shellfish conceptual ecological submodel for the southeast Florida coast.

sizes. Third, gear and fishery impacts with critical habitats can reduce the quality and productivity of the environment that supports these valuable fisheries.

Alteration to Inshore Habitat

Urban development has altered habitat along the entire SEFC from St. Lucie Inlet to Biscayne Bay. The natural shoreline consisting of intertidal mangrove wetlands has been replaced with fill and seawalls. Residential islands have replaced bay water at many locations within the northern bay. Except for the Oleta River and Virginia Key areas, north Biscayne Bay has been almost entirely bulkheaded. Construction of the Intracoastal Waterway dredged a navigation channel inside of the barrier islands through the full length of the coast, altering water circulation patterns. Natural inlets through the barrier islands have been deepened and stabilized and new inlets constructed, with the result of introducing marine waters and altering the nature of estuarine and freshwater waterways. Construction and operation of a system of freshwater canals throughout South Florida has drastically altered the timing and amount of freshwater inflow to estuarine and coastal waters. The net result is that the entire coastline presently exists as an engineered structure that is closely managed to maintain the functioning of coastal municipalities and upstream agricultural lands.

The effect of development on the St. Lucie Estuary has been to alter the timing, distribution, quantity, and quality of freshwater inflow (Sime, 2005). Construction of the regional network of drainage canals greatly expanded the estuary's watershed. In particular, the C-44 canal artificially routes freshwater from Lake Okeechobee into the estuary and, as a consequence, the estuary receives large inflows of freshwater and nutrients from the lake when there is a need to draw down the water level in the lake. Regulatory freshwater releases from Lake Okeechobee and stormwater releases within the watershed alter estuarine salinity, impose increased loads of nutrients and contaminants, and increase turbidity and color in the water column.

Development has dramatically altered the ecology of the Lake Worth Lagoon (Crigger *et al.,* 2005). Historically, Lake Worth was a freshwater lake, receiving inflow from wetlands along its western edge and isolated from coastal waters behind a barrier island that extended along about three quarters of the coastline of Palm Beach County. In 1877, a stable inlet was constructed, providing a permanent connection between the lake and the ocean. Subsequently, a canal was dredged to connect the northern end of the lake to Jupiter Inlet. A second permanent inlet was opened in 1917, and, in 1925, the West Palm Beach Canal was completed, connecting the lake as an outlet to the regional system of water management canals. Approximately 65 percent of the natural shoreline has been replaced with bulkheads and seawalls. The quality of the inshore habitat remaining in the lagoon is affected by the quantity, quality, and timing of freshwater inflows from the water management canal system and ongoing marine construction activities.

Biscayne Bay has been altered both as a result of major changes to the hydrology of its watershed, dredge, and fill to create new islands or increase the elevation of existing islands, construction of seawalls, dredging of navigation channels, and opening new inlets (Browder *et al.,* 2005). Most of the structural changes occurred in the bay from Rickenbacker Causeway north, but hydrologic changes affected the entire bay. Construction of the major canals through the Everglades and dredging natural tributaries has lowered water tables and reduced water storage in the watershed and decreased groundwater flow into the bay. Combined with urban development, this has increased the velocity of stormwater runoff and inputs of nutrients and contaminants to the bay. The dredging of inlets at Haulover and Government Cut increased the connection between the northern part of the bay and the ocean. As a result of these alterations, Biscayne Bay has changed from an estuarine to a more marine system. Nevertheless, parts of the northern bay and most of the southern bay are still productive, ecologically interesting, and beautiful areas. Water quality in the bay has been improved over the last 30 years as result of eliminating direct discharge of sewage into the bay and other pollution control measures; however, inputs of nutrients, trace metals, organic chemicals, and suspended sediments remain a concern.

Non-Native Species

The non-native lionfish is a threat in Biscayne Bay and the coastal marine ecosystem. This highly invasive species is altering the structure of native reef fish communities by out-competing native reef organisms and reducing forage fish biomass (Morris and Whitfield, 2009). Their venomous protective spines, aggressive feeding habits, unique reproduction, and lack of predators all contribute to their competitive advantage. Impacts from lionfish could include direct competition with groupers for reef fish and crustacean pret (Ruiz-Carus *et al.,* 2006; Albins and Hixon, 2008; Morris and Atkins, 2009). Because of its rapid increase and venomous spines, lionfish could potentially disrupt the ecological balance of ecosystems and pose a danger to divers and fishermen (Ruttenberg *et al.,* 2012).

Disease

Disease exerts a significant influence on faunal populations in the Caribbean region. The viral epidemic that struck the long-spined sea urchin in 1983-1984 may be the best known example. This epidemic decimated urchin populations throughout the Caribbean, and the sudden loss of a major herbivore in the food web contributed to a shift in dominance on many reefs from coral to macroalgae. More recently, a viral disease, PaV1, has become widespread in the spiny lobster population. This disease increases mortality primarily in juvenile lobsters, and the consequences of this epidemic are not yet known (Butler *et al.,* 2008).

Mechanisms of Change—Pressures

Fishing

Precise data on trends in coral reef fishing effort, combining both commercial and recreational activities, do not exist, but trends are suggested in state-wide fishing statistics and numbers of registered boats. In 2001, for example, an estimated 6.7 million recreational fishers took 28.9 million marine fishing trips in Florida and caught 171.6 million fish, of which 89.5 million (52 percent) were released or discarded (U.S. Department of Commerce, 2002). From 1964-2010, the number of registered recreational boats in southern Florida grew by more than 500 percent, while the number of commercial vessels grew at a much lower rate, about 150 percent. Many of these vessels are used for fishing and for non-extractive activities, such as sailing, sightseeing, transportation, snorkeling, and SCUBA diving.

Increased fishing fleet size has been accompanied by a number of technological advances that have approximately quadrupled average fishing power, i.e., the proportion of stock removed per unit of fishing effort (Gulland 1983; Mace, 1997; Quinn and Deriso, 1999). These advances include improvements in fishing tackle, hydroacoustics (depth sounders, fish finders), navigation (charts and global positioning systems), communications, and inexpensive, efficient, and more reliable vessel and propulsion unit designs (Bohnsack and Ault, 1996; Ault *et al.,* 1997, 1998, 2005a). These fishing trends raise concerns for fishery sustainability and persistence of the coral reef ecosystem.

Results of the analysis by Ault and Franklin (2011) of fisheries-dependent data for the species of the coral reef complex indicate declining landings balanced by decreased fishing effort. For eight of 19 species for which data are available, there was no significant decline in harvest or effort in the recreational fishery covered by the MRFSS survey data for the period 1990-2009. For 11 reef fish species, the headboat survey data showed a decline in landings by 85 percent between 1990 and 2006, but this coincided with a 50 percent decrease in fishing effort by headboats (angler-days). Landings in the commercial fishery, for six of the reef fish species plus the aggregate category of "grunts," declined by 73 percent between 1990-2006. It is unclear if this decline reflects a decrease in effort in the commercial fishery because no estimates of annual fishing effort could be made. For angelfish, which is exploited for the marine aquaria market, both the landings and number of trips declined in a way that suggests an unchanged trend in landings per trip.

Altered Freshwater Inflow

Freshwater inflow affects conditions in the downstream estuary. The rate of inflow establishes salinity gradients, temperature gradients, and gradients in turbidity and nutrients. High rates of freshwater inflow associated with regulatory releases from the regional water management system degrade the nursery function of inshore habitats (Crigger *et al.,* 2005; Sime, 2005; Ault *et al.,* 2003). The sudden introduction of a large volume of freshwater into a lagoonal estuary can block access by marine ichthyoplankton to the estuarine habitat. Exposure to low salinity water can induce eggs and larvae to settle prematurely or in inappropriate habitats. In the extreme, exposure to salinity outside of an organism's range of tolerance can lead to death. Freshwater inflows introduce land-based pollutants into the estuary. Large regulatory releases into the St. Lucie Estuary have been linked to a range of fish health problems and abnormalities (Sime, 2005). Large freshwater flows can also carry sediments that are then deposited in the estuary, degrading benthic habitats near the point of inflow (Crigger *et al.* 2005). Santos *et al.* (2011) demonstrated landscape fragmentation in areas of canal outflows.

The relationship between pink shrimp and salinity suggest that water management affects inshore pink shrimp abundance. Laboratory trials with growth and survival of small juvenile pink shrimp from western Florida Bay were significantly related to salinity (Browder *et al.,* 2002). Indices of pink shrimp abundance based on Tortugas fisheries data were significantly related to indices of freshwater flow from the Everglades (Browder, 1985; Sheridan, 1996). Meta-analyses of prominent fauna in Florida Bay found pink shrimp were more closely correlated with salinity and seagrass than other species examined (Johnson *et al.,* 2002a, 2002b, 2005). Based on the historical record from western Florida Bay, mean fall (September/October) densities of juvenile pink shrimp were significantly negatively correlated with salinity within the range 28-45. The salinity of seawater is considered to be 35. Salinities greater than 35 indicate that the combination of freshwater inflow and local rainfall are not sufficient to replace water loss from evaporation, even with seawater mixing.

Coastal Construction

In the future, sea-level rise will indirectly drive continued alteration of inshore habitats along the SEFC. For the most part, the urban areas along the coast are completely built-out. The remaining natural shoreline is protected in parks and preserves, and regulations are in place to protect inshore habitats from further destruction. However, as rising sea levels degrade and overtop existing structures, resulting in flooding of developed areas, the response will be to repair and upgrade the affected structures, leading to an increase in construction and consequent impacts to inshore habitats.

Non-Native Species

Red lionfish, formerly residents of the western Pacific, Red Sea, and eastern Indian Ocean, were first reported in the 1980s along South Florida and are now well established along the Florida Keys, the southeast U.S., and Caribbean (Ruiz-Carus *et al.,* 2006; Morris *et al.,* 2009, Ruttenberg *et al.,* 2012).

Status and Trends

Fish of the Coral Reef Complex

The results of Ault and Franklin (2011) provide a mixed picture of the condition of reef fish and lobster populations. Landings data declined for several of the target species, such as groupers, snappers, and hogfish, but these trends were accompanied by decreases in fishery effort, in particular, a decrease in participation in the headboat and lobster commercial fishery. Comparison of the population statistics, derived from analysis of the size of fish caught, with U.S. federal sustainability benchmarks indicated that all the reef fish, except the greater amberjack, experienced overfishing. Black grouper, mutton snapper, gray snapper, and gray triggerfish were in the poorest condition in this regard. These results provide only a characterization of the condition of reef fish and lobster populations, and they are constrained by their reliance on data only from fished populations.

Analysis of the fisheries-independent survey of the fish community along the mangrove shoreline in Biscayne Bay indicate that the abundance of gray snapper and yellowfin mojarra have been relatively stable over the period 1998-2008.

Caribbean Spiny Lobster

Current heavy exploitation of the Caribbean spiny lobster by both the commercial and recreational fisheries removes a large proportion of the adult animals each year. Throughout its range in the Caribbean and Brazil, annual catch peaked between 1987 and 1997 and is currently in decline. The cause of this decline is largely attributed to overfishing, but environmental factors also play a role (Ernhardt *et al.,* 2011). Ault and Franklin (2011) found that data from the commercial fishery for the SEFC region is consistent with a constant level of landings per trip. There was a decreasing trend in commercial landings between 1990 and 2009, but this might be the result of a decrease in fishing effort.

Pink Shrimp

Results of the fisheries-independent monitoring of pink shrimp in south Biscayne Bay, i.e., Black Point to Turkey Point, are available only for 2002-2007. Over this period, observed shrimp densities in Biscayne Bay either equalled or exceeded their historical baseline (RECOVER, 2010). The 20-year record of catch per trip in the Biscayne Bay bait shrimp fishery suggests a long-term decline in shrimp abundance in Biscayne Bay (Johnson *et al.,* 2012).

Lionfish

Reports of lionfish in South Florida began in January 2009, and between January 2009 and July 2010 there were approximately 500 reported lionfish sightings in the Florida Keys (250 of those were confirmed and removed from sanctuary waters) (Morris and Whitfield, 2009). Since then, both sightings and removal efforts have been continuously increasing. Juvenile lionfish (approximately 30 mm in total length) were observed in spring 2010 at several locations in Florida Bay (Ruttenberg *et al.,* 2012), suggesting a pervasive invasion is occurring across all the habitats of the SEFC marine ecosystem. Blue crab fishermen find lionfish in their traps in Biscayne Bay. The increasing abundance and wider distribution of lionfish in the South Atlantic Bight, Bermuda, Florida, and the Bahamas indicates that lionfish have successfully established breeding populations in the tropical central western Atlantic. They are possibly the first marine fish species to do so.

Topics of Scientific Uncertainty

Insufficient and poor quality data and lack of an appropriate modeling framework have prevented sophisticated evaluations of the sustainability of reef fisheries for the purpose of setting regulations on fishing effort. Generally lacking are the data needed to conduct modern stock assessments, including demographic rates, life history parameters, and historical time-series of age-size structured catches by species, and the associated fishing effort by gear in the recreational or commercial sector (Quinn and Deriso, 1999; Haddon, 2001; Quinn, 2003; Ault *et al.,* 2005a).

A more accurate assessment of the status of reef fish populations could be provided by implementing a fisheries-independent monitoring program with a robust sampling design. The most logical plan extends the efforts of the ongoing NMFS Southeast Fisheries Science Center and University of Miami's Rosenstiel School of Marine and Atmospheric Science reef fish visual diver census program in the Florida Keys (Smith *et al.,* 2011) to include Miami-Dade, Broward, Palm Beach, and Martin counties. This approach would not only provide unbiased estimates of population status in the region of interest but also establish a framework for comparisons of reef fish throughout the Florida Reef Tract. In conjunction with studies to collect detailed life history parameters for coral reef associated fishery species, this approach could provide a robust analysis framework to evaluate the biological status of fishery species. This critical step was initiated under the state and federal supported SEFCRI (Southeast Coral Reef Initiative) program in 2012.

Spatial closures, or "no-take" marine reserves, have not yet been implemented in the MARES SEFC region. No-take marine reserves, e.g., in the Florida Keys National Marine Sanctuary, are significant management tools that have been shown to increase fish number and biomass (Halpern and Warner, 2002; Ault *et al.,* 2005a, 2012) but often represent a threat to fishermen who are concerned about the loss of fishing grounds. Priority areas for spatial closures should be identified through population connectivity studies, as well as habitat characterizations of particular locations. An effective network of no-take zones may require closure of areas outside of the MARES SEFC region to support fisheries management goals.

Information is needed to establish targets for the management of freshwater inflows from the regional water management system. Targets are needed for characteristics of freshwater inflow, i.e., volume, timing, and water quality, that are protective of the nursery function of coastal water bodies. Setting these targets requires knowledge of the functional relationship between freshwater inflow and estuarine environmental parameters that are critical to the nursery function, such as salinity, temperature, and toxin concentrations in waters, and sediments. Alternatively, it may be possible to correlate variations in freshwater inflow directly with variations in metrics of fish health or population, such as catch per unit effort in the case of the pink shrimp fishery in Biscayne Bay (Browder *et al.,* 2005; Johnson *et al.,* 2012).

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Benthic Habitat: Coral and Hardbottom

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In a nutshell

- Coral reefs and hardbottom communities provide a vital habitat to numerous species of fish and invertebrates.
- People value coral reefs and hardbottom communities as a place to find large numbers and varieties of fish, for protecting coastlines, a critical habitat for protected species, an ecosystem with a high biodiversity of species, and for their aesthetic beauty.
- Coral reefs and hardbottom communities are vulnerable to direct physical damage from recreational and commercial activities and from the impacts of human development, e.g., beach renourishment, dredging, port development and, potentially, eutrophication of coastal waters.
- In contrast to the Florida Keys, no wildlife preserves and/or marine protected areas presently exist along the southeast Florida reef tract, which poses a challenge to proactive management.

Overview

The SEFC marine ecosystem consists of a series of offshore reefs and hardground ridges that harbor a rich and diverse marine flora and fauna similar to that found in the Florida Keys (Figure 1). Reefs are separated by sandy plains that are themselves home to infauna and a typical fish and epibenthic invertebrate community. The nearshore and seaward-facing shoreline are sandy and characterized by longshore drift of predominantly carbonate sands in a southerly direction. This longshore drift has generated a series of barrier islands that enclose a lagoon of variable width. Most space on the barrier islands is occupied by urban development, and virtually the entire shoreline (both seaward and lagoon facing) has been more or less severely altered by coastal construction activities. The lagoon behind the barrier islands has been severely modified by dredging of the Intracoastal Waterway, artificial inlets to the sea, and drainage canals from the Everglades. The lagoon is characterized by seagrasses and seasonally-variable cover by macroalgae. Mangroves are a common feature on unaltered lagoonal shorelines and constitute an important nursery habitat for fishes. The mainland adjacent to the lagoon is characterized by dense urban development throughout the SEFC region. Salinity in the lagoon is highly variable and, at times, large plumes of lagoonal waters emanate through the inlets.

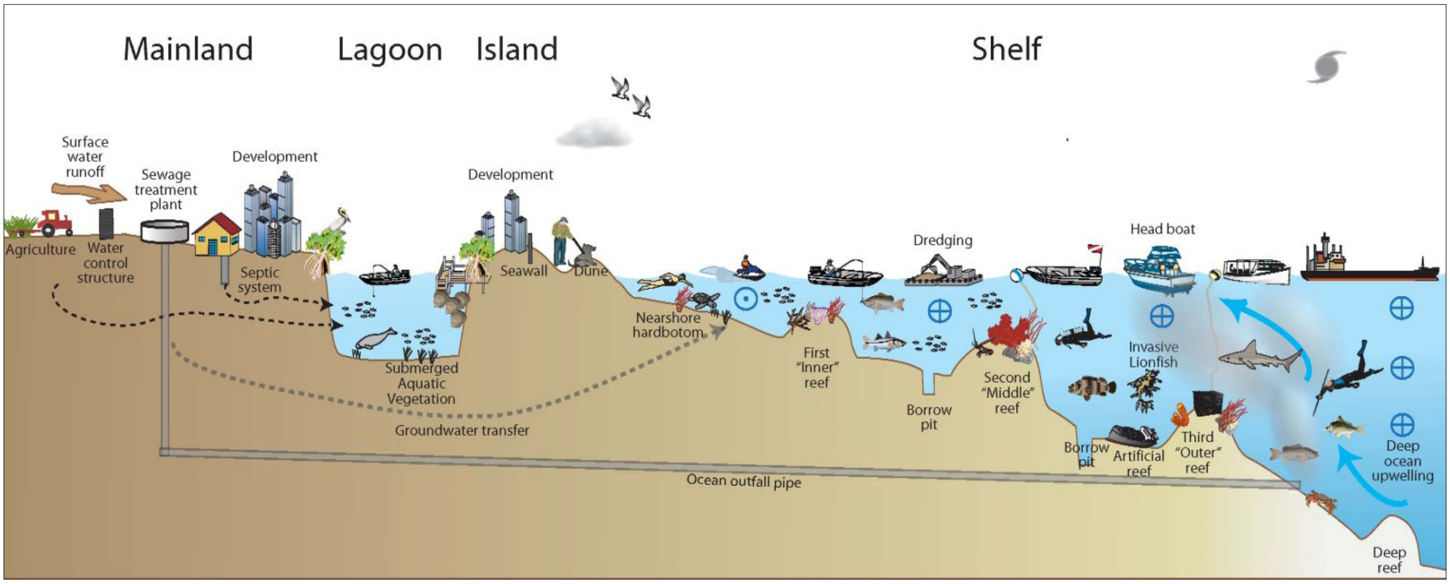

Figure 1. Diagrammatic representation of the *Drivers* and *Pressures* that shape and alter the coral reef and hardbottom habitats of the southeast Florida coast.

Define Resource

Geographic Extent

The coral reefs and hardbottom communities of the SEFC are comprised of a complex of relict Holocene shelf-edge, mid-shelf reefs, and limestone ridges (Lighty, 1977; Banks *et al.,* 2007, 2008). The linear, mostly continuous reef/ridge structures span the continental coast of southeast Florida from offshore West Palm Beach (26°43´N) southward to offshore South Miami (25°34´N), a distance of ~125 km (Banks *et al.,* 2007, 2008; Finkl and Andrews, 2008). These pre-existing structures, along with the present-day biological/physical conditions of the SEFC, allow formation of hardbottom areas, patch reefs, and worm reefs that support rich and diverse biological communities of octocoral, stony coral, macroalgae, and sponge assemblages (Moyer *et al.,* 2003; Banks *et al.,* 2007, 2008). An estimated 19,653 km^2 of inshore area (<18.3 m water depth) exists in southeast Florida that could potentially support shallow-water coral reef ecosystems and represents one of the largest such areas in the U.S. (Figure 2; Rohmann et al., 2005; Banks et al., 2008).

The reefs are positioned <3 km from the highly urbanized centers and rapidly developing coastal areas of southeast Florida where nearly a third of Florida's total population of 16 million resides. Despite their vulnerable location, these reefs possess high economic value by supporting local/regional tourism, fishing, and diving industries and providing natural *Ecosystem Services* such as coastal protection from severe storms. Only recently have the reefs of the SEFC received significant scientific research and resource management attention, yet are likely to become increasingly stressed from continued population growth, coastal development, and climate change (Dodge and Helmle, 2003; Moyer *et al.,* 2003; Collier *et al.,* 2007).

The reefs of southeast Florida are comprised of three shore-parallel, sequentially deeper terraces named the "inner," "middle," and "outer" reefs and also a shallower, "nearshore

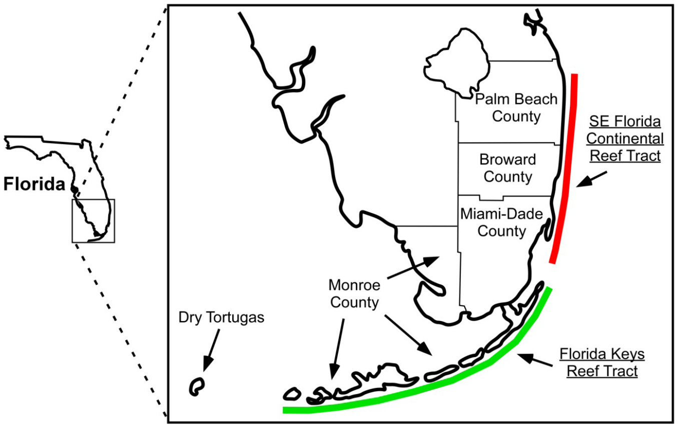

Figure 2. Geographic extent of the southeast Florida reef tract.

ridge complex" (Moyer *et al.,* 2003; Banks *et al.,* 2007). In some instances linear, yet discontinuous "intermediate ridges" exist in the sandy plains between the major reef lines and often form topographic highs of a few meters (Duane and Meisburger, 1969a, 1969b; Raymond, 1972; Shinn *et al.,* 1977; Banks *et al.,* 2007, 2008). Collectively, these structures have been termed the "southeast Florida reef tract" by Banks *et al.* (2007) and are currently distinguished from the better known Florida Keys reef tract located farther south. Despite the geomorphological distinctions between the two reef tracts, they are linked by the northward-flowing Gulf Stream and its dynamic eddies, shingles, and countercurrents.

The SEFC reefs are above 25°N and, therefore, considered a high-latitude system. As a result, cold weather fronts, occasional upwelling, and severe wave action and turbidity (Goldberg, 1973; Jaap and Adams, 1984) in the region lead to low cover of reef builders and reduced reef accretion (Moyer *et al.,* 2003). Presently, the reefs are colonized by a tropical fauna characteristic of west Atlantic/Caribbean reef systems. Stony coral cover is low (~3-6 percent among all reefs), except for a few higher density areas and patches of *Acropora cervicornis*; however, rich communities including mixtures of algae, soft corals, zoanthids, and sponges are more common and thrive in the region.

Low-relief hardbottom communities are a key component of SEFC coastal habitats, in addition to coral reefs. Hardbottom habitats in the southeast Florida reef tract can be found adjacent to the mainland at depths from <1 m to >20 m. Nearshore hardbottom communities are characterized by limestone platform with locally strong, undulating morphology consisting of lithified Pleistocene Anastasia Formation (shelly sands) or early Holocene beachrock ridges. This hardground can be covered by a thin layer of sediments and harbors a similar fauna to the shallow reefs: a sparse mixture of stony corals, soft corals, macroalgae, and sponges. As in the Florida Keys, any of these communities are found on remnant, low-profile habitats lacking significant zonation and topographical development (<1 m of vertical relief) in areas where sediment accumulation is <5 cm (Lirman *et al.,* 2003). These habitats, which can be important nursery habitats for lobsters, are characterized by low coral cover and small coral colony size (Blair and Flynn, 1999; Chiappone and Sullivan, 1994; Butler *et al.,* 1995).

Role in Ecosystem

The coral reef and hardbottom submodel of the SEFC is linked to several other *State* submodels, mainly by:

- Beaches and natural shorelines
- Inland waterways
- Offshore marine waters adjacent to the SEFC

In this section, the interactions of this submodel with the other submodels will be explained.

Beaches and Natural Shorelines

Due to their three-dimensional structure, coral reefs provide protection for beaches and natural shorelines. Although the reefs in southeast Florida do not break the water surface in most areas, the nearshore ridges and inner reef cause sands to pond behind them and, therefore, provide an efficient barrier to offshore sand migration, directly contributing to beach preservation. The shallow, nearshore hardground ridges and reefs serve as wave-breaks in stormy and high-swell conditions. Without reefs, beaches and shorelines would experience more direct physical damage from tropical storm waves and surge. Increased beach erosion by sediment loss and redistribution would also likely occur.

Inland Waterways

The coastal waters of the SEFC interact with upland water through nine tidal inlets plus the wide and shallow "safety valve" opening to Biscayne Bay (Figure 3; Lee, 2012). The two systems exchange water through ebb and flow that can be altered by processes such as increased water runoff due to greater precipitation or swells formed by low-pressure systems (Banks *et al.,* 2008). Fresh water discharge into the coastal waters results in a loss of fresh water supplies on land and ecosystem damage to the marine water bodies that receive the water (Lee, 2012). South of Palm Beach, ocean outfalls discharge secondary treated sewage effluent. This leads to a loss of hundreds of millions of gallons of fresh water supply daily and injects large quantities of nutrients and organic matter into the coastal waters. Algae blooms can occur as a result and threaten the health of coral reefs and the ecosystem (Lee, 2012). Thus, the coastal water's

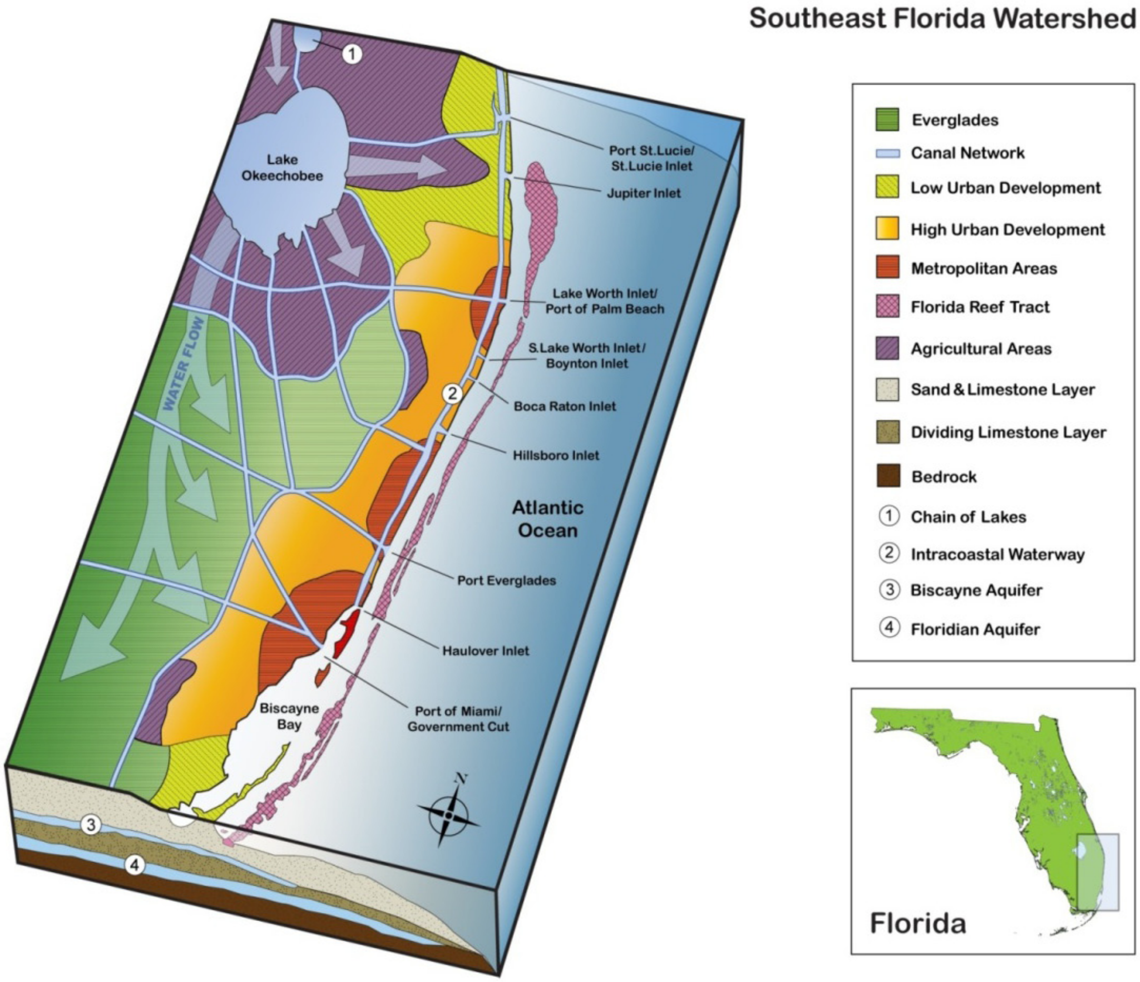

Figure 3. Inland waterways of the southeast Florida coast.

influence on the inland waterways is mainly the loss of fresh water, while the inland waterways bring nutrients and organic matter into the coastal waters.

Offshore Marine Waters

The waters of the SEFC are connected with the Gulf of Mexico and the Gulf Stream in the Atlantic through the Florida Current. This current plays an important part in the North Atlantic Sverdrup circulation (Leetmaa *et al.,* 1977) and global thermohaline circulation (Gordon, 1986). The Loop Current in the Gulf of Mexico brings water from the Florida Keys, West Florida Shelf (Hitchcock *et al.,* 2005; Sponaugle *et al.,* 2005), and upstream river sources such as the Mississippi River to the SEFC (Ortner *et al.,* 1995). Frontal eddies in the Straits of Florida can originate from the Gulf Stream, particularly in the Florida Keys region. Eddies that leave the SEFC region grow rapidly to dimensions of 100-200 km in just a few days (Lee, 2012). Those eddies bring nutrients to the outer shelf and, therefore, enrich marine ecosystem development from Florida to Cape Hatteras (Lee *et al.,* 1991).

The SEFC region is connected to the other Florida model subregions primarily as a downstream recipient. However, larval connectivity from the SEFC region towards the Florida Keys has been demonstrated by DeBiasse *et al.* (2010) and, therefore, all ecosystems along the entire SEFC should be considered intricately connected by a web of oceanographic and genetic connections. The currents will mainly influence the water quality of the other submodels but could also facilitate recruitment of organisms from one submodel to the other.

Key Attributes

People value coral reef and hardbottom ecosystems for the following services and source materials they provide:

- Productivity
- Recreation and aesthetics
- Research and education
- Structure and protection
- Resilience

Productivity

Fishing is an important recreational activity in southeast Florida with significant financial impact on the marine industries. The International Game Fish Association's Fishing Hall of Fame in Dania Beach indicates very well how important this sport is to the local community. Fish and seafood make up an important part of the diet of people living in the region, leading to significant extractive use of the local marine resources. Trophy fisheries, as well as diving and sightseeing activities, also use local fish and other marine life stocks. People tend to have an interest in healthy, growing reefs with high topographical complexity since they provide high levels of productivity that translates into abundant fish and shellfish stocks.

Recreation and Aesthetics

Diverse, productive, and healthy coral and hardbottom habitats also provide maximum enjoyment for snorkelers and divers. The recreational value of coral and hardbottom habitats will increase if a wide variety of different habitat types is widely distributed. This will provide a large number of diverse enjoyment opportunities for repeat visitors, as well as spread the impacts of excessive use over a wider area. Recreational users of the reefs contributed $2.3 billion in sales and $1.1 billion in income from June 2000 to May 2001 and created 36,500 full- and part-time jobs in South Florida (Johns *et al.,* 2001).

Research and Education

The research and education sectors benefit from healthy coral and hardbottom habitats since they can serve as living laboratories for scientists, teachers, and students of all levels of education. Several universities in southeast Florida have marine-based curricula and laboratories situated adjacent to and using the southeast Florida reef tract (e.g., Florida International University's Biscayne campus, Florida Atlantic University's Ocean Engineering Campus, the University of Miami's Rosenstiel School of Marine and Atmospheric Science Virginia Key campus, and Nova Southestern University's Dania Beach campus). Marine high school magnet programs are also maintained by the county school boards. Thus, well functioning coral and hardbottom communities support research and education.

Structure and Protection

The three-dimensional structure of coral reefs provides protection from the impacts of storm waves, surge, and tides, protecting both natural shorelines and property from physical damage. Coral reefs also provide much needed protection for beaches and natural shorelines from erosion. In South Florida, many beachfront hotels and other real estate interests benefit from the indirect protection of coral reefs to their beaches and buildings by providing a barrier to offshore migration of sand.

Resilience

Intact habitat with an intact trophic structure: (1) maximizes the long-term sustainability of the system; (2) increases the likelihood of recovery of threatened species like acroporid corals (the staghorn coral, *Acropora cervicornis,* in particular, has important populations along the southeast Florida reef tract); and (3) increases the resilience potential of the system so that the unique South Florida experience can be enjoyed by both present and future generations.

State: Measurable Ecosystem Attributes

The *Drivers* and *Pressures* characterized by this conceptual model directly impact essential life processes including survival/mortality, growth, reproduction, recruitment, and calcification of various organisms within coral and hardbottom habitats. The end result of these processes determine the *State* of the ecosystem, often characterized and measured in terms of abundance, spatial distribution and extent, diversity and resilience of its fauna and flora, and geomorphic reef structure.

Coral reefs are among the most biologically-diverse ecosystems in the world, and their diversity has long been regarded as a measurable indicator of status and condition (Connell, 1978). Diverse communities (at both the species/taxa and genetic level) are thought to be more resistant and resilient to disturbances and are desired management goals for coral and hardbottom habitats. Whatever the ecological benefits of biological diversity, a more diverse reef system tends to be more visually appealing and provides a higher recreational value to a variety of users. Thus, diversity of reef organisms can be a highly desirable attitude from both a biological and social perspective.

Stony coral abundance (usually estimated as percent cover of substratum) is the most commonly used metric of coral reef status. Coral cover has been observed to decline throughout the Caribbean over the last 30 years and has been used to draw attention to the status and trends of reef systems (Gardner *et al.,* 2003) (refer to Table 1 for a recently estimated relative bottom cover of coral and hardbottom habitats of the SEFC). An abundance of keystone species such as urchins or other bioeroding organisms like boring sponges can also be measured and may provide further insight into coral reef status.

Remotely-sensed data from satellites and aerial photography allow large-scale measurement of the spatial distribution and extent of coral and hardbottom habitats. Data gleaned from these analyses can provide detailed habitat, as well as bathymetric and geomorphological maps, that can be used by resource managers to identify vulnerable areas or temporal changes in habitat extent.

Table 1. Average relative bottom cover for coral reef and hardbottom habitats of the southeast Florida coast (from Banks *et al.,* 2008).

	Palm Beach County		Broward County		Miami-Dade County
	(3)	(1)	(3)	(2)	(3)
Bare substrate	70%	10%	73% (80%)	54%	73%
Macroalgae	1%	66%	4% (4%)	15%	9%
Octocoral	20%	12%	8% (12%)	16%	12%
Porifera	7%	8%	2% (4%)	8%	3%
Scleractinia	1%	2%	13% (0%)	5%	1%
Other	1%	2%	1% (0%)	3%	2%

(1) Foster *et al.* (2006); (2) Moyer *et al.* (2003); (3) FWCC (2006).

The structure and function of coral and hardbottom habitats are closely linked since reef-building corals contribute to the geomorphic structure that is tantamount to healthy and functional coral reefs. This structure serves as the vital habitat for a multitude of reef-associated species (Bell and Galzin, 1984), and reductions in coral cover can cause bioerosional forces to exceed reef accretion. As a result, reduced topographic complexity can decrease a reef's value as a functional habitat (Alvarez-Filip *et al.,* 2009) and affect its ability to keep pace with sea-level rise.

Resilience, or the ability of a system to absorb, resist, or recover from disturbances or to adapt to change while continuing to maintain essential functions and processes, is increasingly recognized as a desirable ecosystem attribute in scenarios where multiple acute and chronic disturbances are common occurrences (Holling, 1973; Nystrom and Folke, 2001), such as is the case in the southeast Florida reef system. Disturbances to this system are both natural (unusual cold or hot events, exacerbated by the high-latitude position of these reefs) and man-made (stresses caused by dredging, coastal construction, runoff, etc.). The Nature Conservancy's Reef Resilience Program (http://www.reefresilience.org/index.html) developed for the Florida Keys also bears relevance to the southeast Florida reef system. It has identified four main components or elements of reef resilience to be considered: (1) representation and replication (and risk spreading) to help increase the likelihood of habitat survival; (2) designation and protection of critical areas vital to survival and sustainability of marine habitats that constitute high priority conservation targets, such as fish spawning aggregations and nursery habitats; (3) preservation of the connectivity among reefs and associated habitats to ensure replenishment of coral communities and fish stocks; and (4) effective management to meet conservation and restoration goals and objectives and, ultimately, keep reefs vibrant and healthy.

Drivers of Change

Changes in the SEFC marine environment share very similar underlying causes as environmental changes in the Everglades and the Florida Keys. The *Drivers* of change act at three scales. Globally, changes arise from the effects of climate change, rising sea levels, and economic and demographic factors that drive changes in land use and exploitation of the region's natural resources. At the scale of the South Florida region, agricultural, municipal, and regional water management practices affect water quality and other characteristics of nearshore coastal water. Locally, human activities along the SEFC impose their own set of *Pressures* on the surrounding marine environment. These can be extractive activities that trigger ecological cascades, cause physical disturbance to reef habitats by careless use, and introduce pollutants and toxins into the water column that eventually impact reef organisms, as well as a myriad of other damaging but usually small additive activities.

Global Scale

Climate change and rising sea levels are important global *Drivers* for the SEFC. Climate and sea level have shaped the ecology and geology of southeast Florida in a comparable, but subtly different way than the Florida Keys (Banks *et al.,* 2007, 2008). Rising sea levels in the early Holocene determined the position of reefs on the SEFC and can be expected to do so in the future. A main determinant in reef health during the Holocene has been the amount of hinterland flooding (Florida Bay, Biscayne Bay) that, as it increased, decreased the vigor of reef growth in the Florida Keys (Lidz *et al.,* 2008). This is likely to have had a cascading effect on the ecosystems of the southeast Florida reef tract, causing a steep decline in coral populations about 4,000 years ago when Biscayne Bay fully flooded. In combination with altered drainage patterns from the Everglades, this interruption of unhindered larval exchange with coral populations in the Florida Keys may have been the reason for the decline of active reef growth that resulted in a depauperate reef-building coral fauna on the southeast Florida reef tract.

Ogden *et al.* (2005) described the effects of climate change on South Florida as follows:

> *"Over the next century, global climate change will interact with and magnify other stresses on South Florida ecosystems (Twilley et al., 2001). Global climate models suggest significant temperature increases and an amplified rate of sea-level rise over the next 100 years with summer highs increasing between 2 degrees and 4 degrees Celsius and winter low temperatures increasing 3 degrees Celsius in South Florida (Twilley et al., 2001). These warmer temperatures will result in fewer freezes, changes in rainfall and storm frequency, and possible shifts in ranges of plant and animal species and alterations in the composition of biological communities."*

Climate change and the stressors associated with this phenomenon are a major source of concern for coral and hardbottom habitats in southeast Florida that commonly live near thresholds for environmental factors predicted to be affected by global climate change. However, it is debatable whether sea level is rising as quickly as feared. Information from U.S. tide gauges suggests that sea-level rise cannot be proven, but that a possible deceleration was observed over the last century (Houston and Dean, 2011). It is, therefore, unclear whether sea-level rise will pose a problem for reefs in the near future.

Worldwide temperatures have increased over the past century by 0.74°C. Strong thermal anomalies leading to bleaching events have been observed with increasing frequency since the 1980s (Baker *et al.,* 2008). It has also been demonstrated that disease outbreaks are favored by unusually warm temperatures (Bruno *et al.,* 2007). In the Florida Keys, a series of repeated bleaching and disease outbreaks have served to reduce the average coral cover from near 15 percent to less than 5 percent, and losses in the dominant reef builders *Acropora palmata*, *A. cervicornis,* and the *Montastraea annularis* complex have been particularly striking (Jaap *et al.,* 2008). Many Florida Keys reefs are presently comparable in coral cover and diversity to those on the higher latitude southeast Florida reef tract. The latter has so far escaped similar depredation of its coral populations due to weather and disease and may, therefore, constitute an important refuge for the Florida Keys reef tract populations.

South Florida experienced a rapid change in economic and demographic factors during the 20th century. Florida was the only state in the U.S. to grow from a population of less than 1 million at the start of the 20th century to a population of over 10 million by the century's end (Hobbs and Stoops, 2002). Most of this population growth occurred in the five southern counties adjacent to coral reefs (Palm Beach, Broward, Miami-Dade, Monroe, and Collier). In 2030, southeast Florida will have a population of 8.5 million, 2.9 million more than in 2010 (Bureau of Census, 2010). The population size of South Florida influences many regional- and local-*scale D*rivers like coastal development, agriculture, wastewater, fishing, and boating.

Regional Scale

Regional-*scale D*rivers include human activities such as agriculture, wastewater disposal, and coastal development, as well as climate-in*duced D*rivers consisting of storms and low-pressure systems.

Human activities on the South Florida mainland influence conditions on the SEFC through their effect on the discharge of freshwater, nutrients, and contaminants into coastal waters of the southeast and southwest Florida shelves. The inputs into the coastal waters of the Southwest Florida Shelf become regional-*scale D*rivers to the SEFC through currents. Effects on the coastal water of the SEFC, on the other hand, are considered *local D*rivers.

Occurring mostly during the 20th century, vast areas of freshwater wetlands were converted to urban and agricultural uses, drastically altering the regional hydrology. To accommodate these changes, a water management system was created to provide flood control and water supply needs to the burgeoning human population. As a consequence, water management, agricultural, and urban land-use practices altered the timing, distribution, quantity, and quality of freshwater discharge into coastal waters. Further changes in inputs from the South Florida region can be anticipated into the foreseeable future.

SEFC marine waters are vulnerable to impacts from human activities outside the South Florida region. Within the Gulf of Mexico, the Loop Current drives a clockwise circulation ending just west of the Dry Tortugas. The Florida Current flows east from this point, then northeast along the Florida Keys and the SEFC before joining the Gulf Stream in the Atlantic Ocean. Via these currents, the SEFC marine waters are vulnerable to impacts from extensive oil and gas exploration and production activities in the Gulf, as demonstrated by the Deepwater Horizon spill of 2010.

Tropical storms regularly strike South Florida, causing direct physical damage in the form of coral fragmentation, dislodgement and overturning, burial, and sediment scouring, as well as secondary damage through light reduction, impairment of filter-feeding activities, and a reduction in salinity due to rainfall and increased runoff (Goreau, 1964). The beneficial impacts of storms include removal of macroalgae and a reduction in seawater temperature that may mitigate bleaching (Man*zello e*t al., 2007). Low-pressure systems, which occur in winter, lead to swells which increase sedimentation and the ebb flow coming from the Intracoastal Waterway through the inlets (*Banks e*t al., 2008). Associated with these low-pressure systems are frequent, unusually cold temperatures that have led to the death of reef organisms in the Florida Keys, but much less so on the southeast Florida reef tract.

Local Scale

Local-*scale D*rivers along the SEFC include water management and agricultural and urban land use practices, as well as boating and fishing. Water management, agricultural, and urban land-use practices have altered the timing, distribution, quantity, and quality of freshwater discharge into the coastal waters. Due to the population boom of the 20th century, fishing and boating have also increased in southeast Florida.

Coastal construction is an impo*rtant* Driver of urban land use. It includes the dredging of harbors, laying of pipes and cables on the seafloor, and restoration of eroded beaches. These activities lead to direct physical damage to coral and hardbottom habitats, as well as to increased sedimentation. Since virtually the entire SEFC is developed and artificially hardened in many places, movements of sediment have been significantly altered. This has caused problems to nearshore hardgrounds by both smothering due to altered sedimentary movements and the requirement for beach renourishment that tends to lead to significant impacts by turbidity and smothering by newly-introduced sediments.

Fishing is a very popular recreational and important commercial activity in southeast Florida. Fishing and harvesting activities, both recreational and commercial, are key components of the economy (Johns *et al.,* 2001). The removal and collection of marine organisms have both direct and indirect impacts on coral and hardbottom habitats. Direct impacts include the targeted removal of organisms such as fish, sponges, lobsters, shrimp, anemones, live rock, etc. Indirect impacts include physical disturbance associated with harvesting activities, fishing and collecting gear, boating, pollution and modifications to the trophic structure, and removal of key organisms that can have cascading impacts on benthic communities. Fishing gear impacts have been documented for both coral reefs and hardbottom communities. These impacts include the removal of sponges and soft corals by drag nets (Ault *et al.,* 1997), as well as trap and line impacts on reef organisms (Chiappone *et al.,* 2005).

Boating in southeast Florida includes commercial ships, cruises, and recreational boating. It causes physical damage to the coral and hardbottom via anchoring and ship grounding, polluting coastal waters and introducing new diseases and invasive species to the region through ballast water release by commercial ships, and fouling organisms travelling on hulls. The physical damage caused by vessel groundings is a major source of disturbance to shallow habitats found within and adjacent to busy shipping lanes. In Florida, impacts by large and small vessels to coral reefs are a significant source of coral mortality and reef-framework modification (Lutz, 2006; *Lirman* et al., 2010).

Southeast Florida is home to three major ports: Port Everglades, the Port of Miami, and the Port of Palm Beach. In 1927, Port Everglades was officially established as a deep-water harbor. It is one of the most active cargo ports in the U.S. and South Florida's main seaport for petroleum products like gasoline and jet fuel. In 2009, Port Everglades opened the world's largest cruise terminal, overtaking the Port of Miami as the most important cruise passenger port in the world (Broward County, 2011). The Port of Miami is planning to dredge its harbor deeper to minus 50 feet until 2014. This will introduce trade with east Asia, resulting in a doubling of the cargo output of this port (Johnson, 2010). This change will not only increase the physical damage to the coral and hardbottom but also introduce new diseases and invasive species from Asia to the SEFC. The Port of Palm Beach is an export port and the fourth busiest container port in Florida. It also has a cruise ship based at the port, the B*ahamas Celeb*ration cruise (Port of Palm Beach District, 2011).

Mechanisms of Change

Of all marine habitats in Florida, the SEFC marine ecosystem is the most severely impacted by urban development and human activities. Stressors are primarily related to construction activities (coastal construction, beach renourishment, dredging for sand-mining and construction purposes, runoff, etc.) and commercial activity related to ports (ship anchoring, ship groundings, ballast water, and pollutants emanating from ships). Recreational activities feature strongly in the perception of the value of the SEFC marine ecosystem, and marine-based tourism accounts from ~$4 billion income per annum in the tri-county area (Miami-Dade, Broward, and Palm Beach counties). Recreational impacts are both direct (fishing, removal of ornamental organisms, breakage of reef organisms, pollution emanating from recreational vessels, etc.) and indirect (construction activities to harbor recreational vessels, ecological cascades triggered by the removal of keystone fish or invertebrate species, etc.).

Natural *Drivers* of ecosystem quality are related to high latitude setting, global change, and introduced species (Figure 4).

Sea-Level Rise

As predicted by many scenarios of future global change, sea-level rise can modify the depth distribution of organisms based on their light requirements. Sea-level rise in South Florida is predicted to be amplified by climate change (Twilley *et al.,* 2001), but evidence to date is elusive (Houston and Dean, 2011). Indirect impacts of sea-level rise, due to impingement of the sea on the developed coastline, would be much greater than direct impacts. Since much of southeast Florida is low-lying, a rise in sea level and the likelihood of flooding in residential and commercial areas would lead to increased shoreline protection activities. The associated construction would likely lead to even more significant environmental alterations in the nearshore environment that would likely have cascading effects on the further offshore ecosystems.

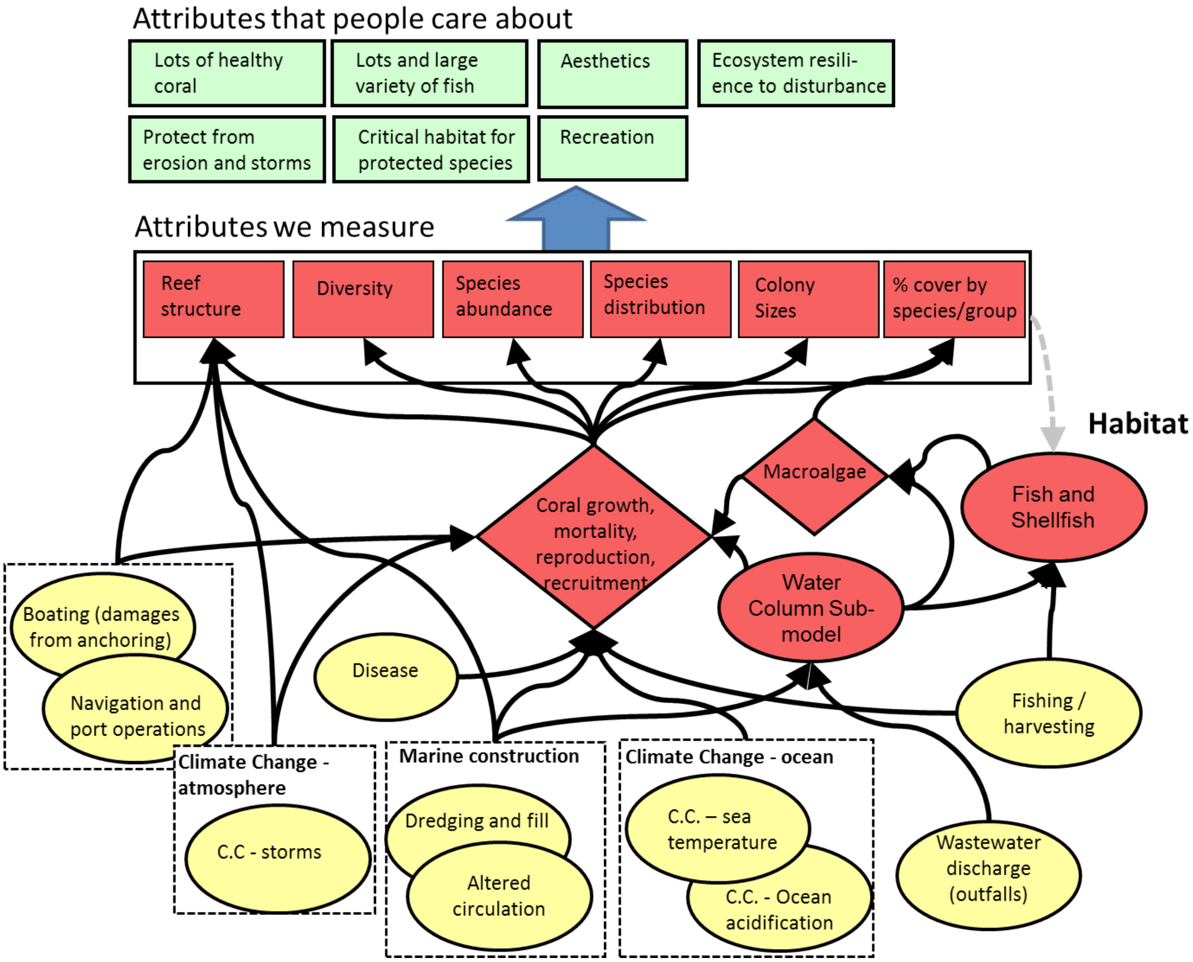

Figure 4. The coral and hardbottom conceptual ecological submodel for the southeast Florida coast.

Temperature Extremes

Both high (>30°C) and low (<15°C) temperatures have been shown to cause coral bleaching (i.e., expulsion of symbiotic dinoflagellates) and, if prolonged, significant mortality to corals and other benthic organisms (Van Oppen and Lough, 2009). Coral bleaching and mortality on the Florida reef tract have been recorded during the 1998 and 2005 bleaching events. Cold-water mortality of corals and other organisms was observed historically (Davis, 1982; Jaap and Sargent, 1994) and, more recently, in the winter of 2010 (Lirman, personal observation). The two *Drivers* which influence seawater temperature are climate change and storms. Seawater temperatures are predicted to rise due to climate change (Twilley *et al.,* 2001). Storms, on the other hand, can lower seawater temperature (Manzello *et al.,* 2007).

Water Quality

Water quality includes acidity, nutrients, salinity, turbidity, light, and aragonite saturation. Decreased water quality can lead to lower growth rates, coral mortality, and a reduction in reproduction, recruitment, and calcification. Land-based sources of pollution are the most immediate mechanism of change that is of concern.

Increases in atmospheric CO_2, as predicted in global change scenarios, will increase the acidity of the seawater. This will result in reduced calcification and potentially even skeletal dissolution (Kleypas *et al.,* 1999; Andersson *et al.,* 2005; Cohen and Holcomb, 2009). Effects would be similar in western Florida, the Florida Keys, and southeast Florida ecosystems. Aragonite saturation (Ωarag) decreases when the pH of the water decreased, as predicted by climate change. Hall-Spencer *et al.* (2008) showed that organisms with aragonite skeletons are absent at a mean Ωarag ≤2.5. This leads to the prediction that these organisms are not able to form their skeletons at these concentrations.

Nutrients

Increased nutrients can have both direct and indirect impacts on benthic organisms (Szmant, 2002). Direct impacts include the impairment of calcification and growth in stony corals under high nutrient conditions (Koop *et al.,* 2001). Indirect effects include the disruption of the coral-zooxanthellae symbiosis and a reduction in the translocation of carbon to the host (Fabricius, 2005), increased phytoplankton in the water column leading to reduced light penetration, and even toxicity (Brand and Compton, 2007; Butler *et al.,* 2005; Boyer *et al.,* 2009) and enhanced growth of macroalgae, a key space competitor in coral reefs and hardbottom habitats (Lapointe and Clark, 1992; Lapointe *et al.,* 2002, 2004). Wastewater discharge and agriculture are the two anthropogenic *Drivers* which can add additional nutrients to the natural nutrient load of the ocean.

Salinity

Changes in salinity in either direction can lead to increased or decreased respiration, depending on the coral species (Vernberg and Vernberg, 1972). Reduced salinity can also lead to local coral bleaching (Brown, 1997). It is generally agreed that most scleractinian corals can survive only small variations in salinity, with death resulting when salinity drops below 25 percent (Edmondson, 1928) or increases above 40 percent (Jokiel *et al.,* 1974). The SEFC has nine tidal inlets which connect the ocean to the inner coastal waters. Heavy rainfall can lead to the increased outflow of freshwater, reducing the salinity around the inlets. Changes in atmospheric heat content are predicted to change global rainfall patterns, leading potentially to increased dryness in Florida. This would, however, be counteracted by the increased moisture content of the tropical atmosphere delivering more severe precipitation associated with cyclonic disturbances. Hence, while mean terrestrial runoff may decline in the future, stormwater delivery and pulsed runoffs that tend to bring pollutants and nutrient pulses to reefs may indeed increase.

Turbidity

Turbidity is caused by storms and sedimentation and influences the amount of light that corals receive. Aller and Dodge (1974) and Dodge *et al.* (1974) discovered that coral growth slows down when the water becomes more turbid. However, other scientists have concluded that turbidity does not prohibit coral growth and may even increase coral growth (Roy and Smith, 1971; Maragos, 1974a, 1974b). A study conducted in the Florida Keys found that coral cover is less in more turbid water (Yentsch *et al.,* 2002).

Toxicity

Toxification can result from wastewater or from phytoplankton blooms. The following chemicals commonly found in wastewater induce toxic effects on corals and other reef organisms: polychlorinated biphenyls, metals, chlorine, phosphate, pesticides, and petroleum hydrocarbons (Pastorok and Bilyard, 1985). Cyanobacteria blooms can be directly toxic to corals and indirectly affect them by stimulating the growth of bacteria. This can lead to corals suffering from black band disease (Gantar *et al.,* 2009). In southeast Florida, a bloom by the cyanobacteria *Lyngbia* spp. caused significant coral mortality. Toxins from phytoplankton can be carried up the food web by zooplankton and even lead to the death of fish, whales, dolphins, and sea birds (Steidinger, 1983; Burkholder and Glasgow, 1995; Anderson and White, 1992; Gerachi *et al.,* 1989; Work *et al.,* 1993), changing the community that surrounds coral reefs.

Sedimentation

Sedimentation is recognized as an increasing source of disturbance to coral and hardbottom habitats around the globe experiencing rapid population expansion, watershed modification, and coastal construction (Wilkinson, 2002, 2008). All of these *Drivers* are present in southeast Florida. Sedimentation can impact coral reef and hardbottom organisms through light reduction, smothering and burial, and toxicity (Bastidas *et al.,* 1999; Fabricius, 2005). Reductions in coral growth, photosynthesis, reproductive output, lesion regeneration, feeding activities, and recruitment have all been documented for corals under high sediment loading (Rogers, 1983, 1990; Riegl, 1995; Babcock and Smith, 2000; Lirman *et al.,* 2003; Philipp and

Fabricius, 2003). Sedimentation tends to be increased by the artificial alteration of shorelines and coastal construction activities.Pollution

Pollution impacts caused by human activities on coral and hardbottom habitats have been associated with oil spills (Jackson *et al.,* 1989), urban and agricultural stormwater and overland runoff (Glynn *et al.,* 1989; Jones, 2005; Fauth *et al.,* 2006), as well as physical impacts caused by solid waste disposal and others (Peters *et al.,* 1997). Coastal development, boating, and fishing are also anthropogenic *Drivers* that cause pollution. The impacts of oil spills may include tissue and larval mortality, as well as sublethal impacts on photosynthesis and reproduction (Haapkylä *et al.,* 2007).

Disease

Diseases have been implicated as one of the main causal factors in the drastic decline in the abundance and distribution of corals recorded over the past three decades in Florida and elsewhere (Aronson and Precht, 2001; Kim and Harvell, 2002; Richardson and Voss, 2005). Many (if not most) of the epizootic agents and transmission pathways that affect soft and hard corals and sponges have not been fully described. Nevertheless, studies have found that increased temperatures are related to disease prevalence, especially after bleaching events (Brandt and McManus, 2009), that human pathogens may cause disease in nearshore corals (Sutherland and Ritchie, 2004), and that the predatory and territorial activities of snails, polychaete worms, and fish may be a mechanism for the inter-colony transmission of disease vectors (Williams and Miller, 2005).

Physical Damage

Physical damage can result from storms, fish, boats, or fishing. Hurricanes can cause anything from minor colony fragmentation and scouring to severe fragmentation of reef framework (Lirman and Fong, 1997; Gardner *et al.,* 2005; Gleason *et al.,* 2007). Fish prey on corals or damage them through other means like territorial activities. Boating activities, both recreation and commercial, are a major source of physical impacts to coral and hardbottom habitats (Precht, 2006 and references therein). Physical damage to benthic organisms and habitats can be caused directly by the impact of vessels' hulls, keels, propellers, and anchors, or indirectly through the movement of dislodged coral colonies and the shifting of sediments and rubble created during the initial impact. Damage to coral reefs can range from superficial, where only the living surfaces of corals are damaged, to structural where the geomorphologic reef matrix is fractured and exposed (Lirman *et al.,* 2010). Fishing gear impacts have been documented for both coral reefs and hardbottom communities. These impacts include the removal of sponges and soft corals by drag nets (Ault *et al.,* 1997), as well as trap and line impacts on reef organisms (Chiappone *et al.,* 2005).

Macroalgae and Phytoplankton

Macroalgae and phytoplankton interact with coral and hardbottom habitats as *Drivers* and *Pressures*. Macroalgae overgrowth of corals under high nutrient and low grazing conditions has been implicated in the phase shift from coral-dominated to algal-dominated communities throughout the world (Hughes, 1994; McCook, 1999; Hughes *et al.,* 2007). Human activities can result in the release of: (1) top-down control of macroalgae by modifying the trophic structure of coral and hardbottom habitats which reduces the abundance of key herbivores (e.g., parrotfish); and (2) bottom-up control of macroalgae by increasing nutrient availability. The rapid growth of macroalgae under these scenarios can result in coral mortality through shading, sediment accumulation, smothering, and allelopathy, as well as reduced recruitment and survivorship of coral larvae (Lirman, 2001; McCook *et al.,* 2001; Nugues and Roberts, 2003). Elevated phytoplankton populations may stress hermatypic corals in two ways. First, reduced light penetration affects coral nutrition growth and survival through negative impacts on the zooxanthellae (Smith *et al.,* 1981). Second, increased water-column production often favors the growth of benthic filter-feeders such as sponges, bryozoans, and tunicates, which outcompete corals for space (Maragos, 1972; Maragos and Chave, 1973; Birkeland, 1977). Hardbottom cryptofauna may also increase in biomass (Brock and Smith, 1983).

Fish

Herbivores, predators, shellfish, and invasive species like algae and phytoplankton interact with the coral and hardbottom as *Drivers,* as well as *Pressures*. While the removal of herbivores (e.g., parrotfish, surgeonfish, and sea urchins) is not a problem in South Florida where fishing activities are highly regulated, overfishing of herbivores has resulted in increases in macroalgae in other areas of the Caribbean (Hughes, 1994). The removal of predators may result in an increase in the abundance of damselfish that can result in increased coral mortality. This is due to their territorial activities that include killing coral tissue to grow macroalgae (Kaufman, 1977). Another cascading effect of predator removal, in this case lobsters, may be the increase in the abundance of corallivorous gastropods (*Coralliophila abbreviata*) that cause significant tissue mortality on colonies of reef-building corals and are known prey items for this once abundant taxon (Johnston and Miller, 2007).

Invasive Species

Invasive species can alter the ecosystem balance of a region. In South Florida, the lionfish is a major threat to coral reef communities. Many adults and juveniles have been found, which indicates that they are established and reproducing in the region (Hare and Whitfield, 2003). Lionfish could impact the native SEFC ecosystem through predatory interactions. Lionfish feed on a wide variety of smaller fish, shrimp, and crabs which are abundant in southeast Florida (Fishelson, 1975, 1997; Sano *et al.,* 1984; Wenner *et al.,* 1983). Predation on lionfish is thought to be limited because there are only a few predators within the native range (Bernadsky and Goulet, 1991). Moreover, predators along the southeast U.S. have no experience with the venomous spines of the lionfish (Ray and Coates, 1958; Halstead, 1965).

In response to the lionfish invasion, NOAA made a flyer informing divers about the threat lionfish posed and asked them to report their sightings of lionfish (Hare and Whitfield, 2003). Morris *et al.* (2010) made a population model of the lionfish that suggested the lionfish population could be controlled if 27 percent of the adult population was fished every month. As a way to implement this scenario, Morris *et al.* (2010) further suggested the use of lionfish as food for humans. NOAA responded by publishing an “Eat Lionfish” pull card informing the public and restaurants of the advantages of including lionfish in their diet: Eat sustainable, eat lionfish!

Water Management

In southeast Florida, water quality monitoring is limited to inland waters (Trnka *et al.,* 2006; Caccia and Boyer, 2005; Torres *et al.,* 2003; Carter, 2001). There are no long-term data available for ocean waters, but the Broward County Environmental Protection Department began a coastal water quality monitoring program in 2005 (Craig, 2004). Around Port Everglades, nutrients, chlorophyll, salinity, dissolved oxygen, and pH are measured monthly at three different sites (Banks *et al.,* 2008).

Different agencies work together to implement sustainable water management in southeast Florida. These agencies include the South Florida Water Management District (SFWMD) and its Water Resources Advisory Commission (WRAC). The SFWMD is a regional governmental agency in charge of the water resource. Created in 1949, the agency is responsible for managing and protecting the water resources of South Florida by balancing and improving water quality, flood control, natural systems, and water supply. Its goal is to manage stormwater flows to rivers and freshwater discharge to South Florida’s estuaries in a way that preserves, protects, and, where possible, restores these essential resources (SFWMD, 2011a).

All of the SFWMD’s coastal projects focus on wetlands; nevertheless, some of the measurements they implement also benefit coral and hardbottom habitats. The wetlands in South Florida have a severe problem with extreme salinity fluctuation, pollution, nutrients, wastewater, and stormwater runoff. The SFWMD wants to improve their state by dredging new channels, building reservoirs and stormwater treatment areas, and through education (SFWMD, 2011b; Dupes, 2004). For the Lake Worth Lagoon, they’ve even gone a step further by implementing and enforcing regulations to eliminate sewage discharges and the building of artificial reefs (Palm Beach County Department of Environmental Resources Management, 2008). All of these measures help the coral and hardbottom communities by lowering their nutrient load and the amount of wastewater and stormwater they receive.

The WRAC is an advisory body to the South Florida Water Management Governing Board and the South Florida Ecosystem Restoration Task Force. Its main purpose is to improve public participation and decision-making in water resource-related topics. For this reason, the members of the Commission come from the following backgrounds: business, agriculture, environment, tribal, government, and public interest (SFWMD, 2011c).

Climate Change

Climate change threatens millions of people and businesses along the SEFC by shifting weather patterns, increased hurricane intensity, and rising seas (South Florida Regional Planning Council, 2008). For these reasons, the South Florida Regional Planning Council wants to take action against climate change. Between 1990 and 2005, green house gas (GHG) emissions increased in Florida by about 35 percent, and a business-as-usual projection to 2025 showed an increase in GHG emissions of 86 percent compared to the 1990 level (Strait *et al.,* 2008). On July 13, 2007, Governor Charlie Crist signed executive orders (07-126, 07-127, 07-128) which required South Florida to reduce its GHG emissions to 80 percent below the level of 1990 by 2050 (South Florida Regional Planning Council, 2008). Recent actions that Florida has undertaken, like the electric utility cap and the adoption of California Clean Car Standards, will lower the increase of GHG emissions to 55 percent of the 1990 level by 2025 (Strait *et al.,* 2008).

Ship Groundings and Anchor Damage

Due to the proximity of reefs to navigational inlets, southeast Florida has a high risk of reef damage due to ship groundings and anchor damage. Fortunately, vessel owners respond well to the damages they cause and carry out reef restoration (Banks *et al.,* 2008). Moffatt and Nichol (2006) completed a study about alternative anchorages at Port Everglades. This study should help federal, state, and local government agencies eliminate shallow anchorages, thereby reducing impacts. Recreational boats anchoring outside of designated areas also cause reef damage. For this reason, over 100 moorings were installed in Broward County. Vessel-related impacts can also be minimized by the availability of high-resolution bathymetry and advances in positioning technology and remote, real-time monitoring of a vessel's position. These techniques allow the establishment of transit corridors for vessels (Banks *et al.,* 2008).

Coastal Construction

Due to a greater conservation ethic by the public and increased awareness of the resources present, coastal construction projects have increased their environmental protection measures in recent years. Broward County, for example, spent about 20 percent of the total construction cost of a recent beach restoration project for environmental protection and monitoring. For the proposed construction of three natural gas pipelines, the reef friendlier technology of tunneling under the coastal shelf was favored over horizontal directional drilling (Banks *et al.,* 2008).

Fishery Regulations

The Florida Fish and Wildlife Conservation Commission (FWC) is authorized by the Florida Constitution to enact rules and regulations regarding the state's fish and wildlife resources. Created in 1999, its goals are to manage fish and wildlife resources for their long term well-being and the benefit of people (FWC, 2012a). Fishing regulations set in place by the FWC include size limits, the amount of fish one is allowed to catch (bag limits), closed seasons, and species which are prohibited to fish. With these measures, the FWC tries to manage the different fish species depending on their conservation needs (FWC, 2012b). Next to the harvest of fish, fishing gear can also have a negative impact on coral and hardbottom habitats. To diminish the physical damage done to coral and hardbottom by lost traps, the FWC has two programs dedicated to removing lost and abandoned traps from state waters (FWC, 2012a).

Status and Trends

Despite having a similar fauna to the Florida Keys, Bahamas, and Caribbean, the community structure of the southeast Florida reef tract is different (Moyer *et al.,* 2003). The major reef builders of the Florida Keys, *Acropora palmata* and the *Montastraea annularis* complex, are both exceedingly rare in southeast Florida; however, living isolated colonies have been reported (Banks, personal observation; Banks *et al.,* 2008). On the southeast Florida reef tract, the majority of colonizable substrate is bare (roughly 70 percent), but relative cover is dominated by macroalgae or octocorals, while stony coral cover is low (<6 percent) as indicated in

Table 1. Isolated patches with higher coral cover exist on the ridge complex offshore central Broward County where a site that is dominated by massive corals has approximately 16 percent cover, and another site with large colonies of *Acropora cervicornis* has ~34 percent cover (Banks *et al.,* 2008).

Significant mortality of corals and other reefal organisms in the Florida Keys over the past few decades have led to an increasing homogenization of the faunas and community structures of reefal organisms in the Florida Keys and the southeast Florida reef tract (Jaap *et al.,* 2008). Today, *Acropora palmata* is rare in the Keys and *Montastraea annularis* complex is also much reduced in frequency and ecological importance. The newly-dominant species in the Florida Keys reef tract, mainly in the genus *Porites* and *Montastrea cavernosa*, also dominate in the southeast Florida reefs (Moyer *et al.,* 2003). Richards *et al.* (2009) have shown genetic connectivity in reef organisms between the Florida Keys and southeast Florida in both directions, indicating that the southeast Florida reef tract is not only a recipient of genetic material and populations, but also a potential source. That, and the lower rate of decline in populations of especially corals, raises the importance of the southeast Florida reef tract as a potential refuge habitat.

Given the unique accretion history and present day environmental conditions of reefs from the SEFC, comparisons to extant *Acroporid*-dominated reefs in other areas of the Caribbean and western Atlantic are difficult. The geologic and stratigraphic records of reefs from the SEFC indicate that *Acroporids* ceased dominating cover 5-7 cal BP (Lighty *et al.,* 1978; Banks *et al.,* 2007). Significant declines and large-scale loss of *Acroporids* have occurred over the past decades in the Caribbean and western Atlantic, largely as result of white band disease (Gardner *et al.,* 2003). In stark contrast, only 1.8 percent of the cover of the *Acropora cervicornis* thickets offshore of Broward County was afflicted with white band disease (Vargas-Angel *et al.,* 2003), and the populations remain vigorous to this day.

The incidence of coral bleaching and disease has been relatively low in southeast Florida since 2004, when data were first collected. That year, 19 diseased coral colonies were identified in the 10 study sites and, in 2005, 21 diseased colonies were identified, 10 of which had apparently been infected in 2004. Nine of those were *Siderastrea siderea* with dark spot syndrome and had recovered by 2005. White complex disease was more prevalent in 2005 (FWCC, 2006). No completely bleached coral colonies were reported, yet partial bleaching was more common than disease (Banks *et al.,* 2008).

Southeast Florida also experienced the Caribbean-wide decrease of the sea urchin, *Diadema antillarum*, which was once reported as being abundant offshore Boca Raton by Goldberg (1973). Recent reports indicate that recovery of this keystone species appears to be lagging in southeast Florida, as well as in the Florida Keys (FWCC, 2006; Banks *et al.,* 2008).

The relationship between sewage contamination and the increased occurrence of bioeroding clionid sponges has been reported on the Florida Keys reef tract (Ward-Paige *et al.,* 2005). Reports (FWCC, 2006) and diver observations indicate that clionids are abundant throughout Broward County, particularly on the ridge complex and inner and middle reefs (Banks *et al.,* 2008). No trends have been reported for Palm Beach and Miami-Dade counties, and thus a lack of understanding regional distributions exists. It is uncertain whether clionids pose a significant threat to southeast Florida coral populations, and investigations are underway (Chaves-Fonnegra, personal communication).

Harmful algal blooms by *Caulerpa* spp. have widely occurred offshore Palm Beach County during the past decade (Lapointe *et al.,* 2006) and, in 2007, spread into northern Broward County. Extensive cyanobacterial blooms of *Lyngbya* spp. have been reported on reefs offshore of Broward County (Paul *et al.,* 2005) and have had a significant impact on reef-associated organisms by smothering and outcompeting recruits of sessile benthos (Lapointe, 1997). Observations by Gilliam *et al.* (2007) revealed that decreased density of sponges and octocorals was caused by significant coverage of *Lyngbya* spp.; however, stony corals did not seem to be affected.

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Benthic Habitat: Seagrasses

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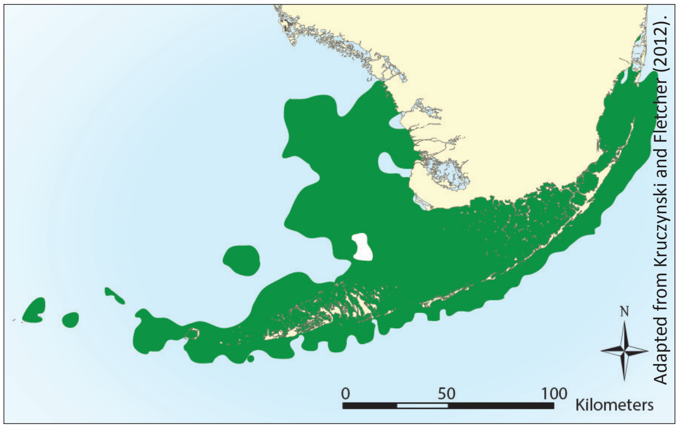
In a nutshell

- Seagrasses provide habitat for fish and invertebrates and play a major role in maintaining water quality by taking up and transforming nutrients.
- People value seagrasses as a place to find large numbers and a variety of fish, for stabilizing sediments, as critical habitat for protected species, and as a natural filter for wastewater and stormwater.
- The damage to seagrasses from recreational and commercial activities can lead to complete loss of seagrass beds in heavily affected areas.
- Proximity to an urbanized shoreline threatens seagrass beds directly from the impacts of coastal construction and indirectly from the effect of altered freshwater inflows on salinity and from eutrophication caused by land-based sources of pollution.

Benthic communities composed of seagrasses and macroalgae are characteristic of shallow coastal waters worldwide; however, few areas contain meadows as extensive as those found in South Florida (Fourqurean *et al.,* 2001). The seagrass beds found in Biscayne Bay and offshore habitats of Dade County make up part of the 14,622 km^2 regional expanse of seagrass beds that extend south and west into Florida Bay and the coastal marine waters surrounding the Florida Keys. This is one of the most expansive seagrass beds on Earth, comparable to the back-reef environment of the Great Barrier Reef in Australia (Lee Long *et al.,* 1996) and the Miskito Bank of Nicaragua (Phillips *et al.,* 1982). Seagrass beds provide key *Ecological Services*, including organic carbon production, nutrient cycling, sediment stabilization, food sources, and habitat structure that enhance local biodiversity (Orth *et al.,* 2006).

At least seven species of seagrasses occur in SEFC: turtle grass (*Thalassia testudinum)*, manatee grass (*Syringodium filiforme)*, shoal grass (*Halodule wrightii)*, three species of *Halophila,* including *H. johnsonii,* which is a federally-listed protected species, and *Ruppia maritima.* Distribution of seagrass species is generally related to water clarity and quality, substrate, salinity level, and variability. *Syringodium filiforme* and *H. wrightii* are common in the northern bay, where salinities are lower and water clarity is diminished due



Adapted from Kruczynski and Fletcher (2012).

Figure 1. Distribution of seagrass beds in the Florida Keys marine ecosystem.

to high freshwater discharge combined with a low flushing rate. Significantly-mixed *Thalassia/Syringodium* beds also exist in north Biscayne Bay. *Thalassia* is most prominent in central and south Biscayne Bay where salinities are higher and more stable and nutrient levels are lower overall.

Large areas of Biscayne Bay support seagrass communities because sediment depth and nutrients are sufficient, water depths are shallow, and water clarity is high. Seagrass has been documented to cover up to 64 percent of the bay bottom (DERM, 1985). There is very little area of bare bottom with sufficient sediment depth to support seagrass except where there has been a physical disturbance such as dredging.

Seagrasses Support Fisheries and Maintain Water Quality

Seagrass beds provide habitat vital to support different life stages of a variety of ecologically important and commercially and recreationally valuable species. Seagrass beds are among the most productive and economically valuable ecosystems (Zieman and Wetzel, 1980; Costanza *et al.,* 1997). The proximity of seagrass meadows to coral reef and mangrove ecosystems provides critical feeding grounds and nursery areas for species who rest on coral reefs or in mangroves as adults, such as pink shrimp, spiny lobster, and grouper (Beck *et al.,* 2001). These associations are essential in maintaining the abundance of some coral reef and mangrove species (Valentine and Heck, 2005).

Seagrasses maintain water quality. They trap sediments produced in other parts of the ecosystem (Kennedy *et al.,* 2010) and decrease sediment resuspension (Green *et al.,* 1997), thereby contributing to clearer water. They are also sites of active nutrient uptake to fuel their high primary productivity; nutrients taken up by seagrasses cannot be used by phytoplankton and macroalgae. The importance of seagrasses to water quality in South Florida was made clear following the seagrass die-off that occurred in Florida Bay in the late 1980s (Robblee *et al.,* 1991). The loss of the nutrient retention and sediment stabilization provided by the dense seagrass meadows of western Florida Bay resulted in orders-of-magnitude increases in turbidity and phytoplankton concentrations in the water column that persisted for a decade following the die-off (Boyer *et al.,* 1999). This decrease in water clarity led to further decline and change in community composition of the seagrasses that survived the die-off (Hall *et al.,* 1999).

Attributes People Care About

Seagrasses in the SEFC support attributes of the marine environment that people care about. These attributes are directly related to *Ecosystem Services* provided by the SEFC marine ecosystem:

- Lots and large variety of fish
- Intact habitat for quick species recovery
- Coastal erosion and storm protection
- Critical habitat for protected species
- Natural filter for wastewater and stormwater runoff
- Carbon sequestration

Lots and Large Variety of Fish

Seagrass beds are important locations for recreational fisherman. Biodiversity is much higher and animal densities are orders of magnitude higher in seagrass beds than in surrounding unvegetated sediment (see Hemminga and Duarte, 2000, for a review).

The money spent on owning and operating private vessels in the region is at least partly motivated by those targeting seagrass ecosystems for their recreational opportunities.

Intact Habitat for Quick Species Recovery

As a vital component of the mangrove-seagrass-coral reef habitat mosaic that makes up the South Florida nearshore marine ecosystem, seagrass meadows are vital to the resilience of the ecosystem to disturbance. Given their ability to stabilize sediments and trap suspended particles, they prevent storm resuspension of sediments, erosion, and the consequent decreases in water clarity that would accompany them; hence, the presence of seagrass meadows protect the coral reefs from disturbance-generated water quality degradation and they protect the shoreline from storm-driven erosion.

Since many of the fish that live on Florida's coral reefs leave the reefs and feed in seagrass beds (Robblee and Zieman, 1984), seagrasses promote healthy reef ecosystems; without the seagrasses, fish stocks on coral reefs may not be able to rebound following disturbances. Many of the commercially-important species also depend on seagrasses at some stage in their life cycle, including pink shrimp, spiny lobsters, mangrove snappers, and queen conch. Without seagrasses, such species could not recover from disturbance.

Coastal Erosion and Storm Protection

By reducing wave height, current velocities, and sediment resuspension, seagrass meadows protect shorelines from erosion, saving coastal communities the tremendous capital they would need to spend to repair erosion of the coastline. In fact, seagrasses are a much more economical means of protecting coastal properties than building seawalls and armoring coastlines with riprap, since seagrass beds require no expenditure of capital for maintenance and can self-adjust to rising sea levels by the accretion of sediments in the seagrass beds. The human-built erosion-control structures require resources to be spent to maintain them and, as the sea level rises, they will need to be redesigned and rebuilt.

Critical Habitat for Protected Species

The world's only listed, threatened marine plant species, Johnson's seagrass (*Halophila johnsonii*), is one of the seagrasses of South Florida that occurs in protected marine waters and estuaries from Key Biscayne northward to the Indian River Lagoon. Seagrass beds of South Florida are essential habitat for the endangered green sea turtle and the West Indian manatee. They also support many threatened species including Nassau grouper and queen conch. Bottlenose dolphins feed extensively in seagrass meadows. Wading birds such as great white herons, great blue herons, little blue herons, great egrets, snowy egrets, reddish egrets, and American flamingos all feed in seagrass-covered shallows.

Natural Filter

Seagrass meadows are among the most active sites of bacterial nutrient cycling in the coastal ocean. Rapid growth rates of seagrasses and associated micro- and macroalgae take up readily available plant nutrients, like dissolved inorganic phosphorus, nitrate, and ammonium, out of the water. The efficient trapping of particles by the seagrasses provides another flux of particulate forms of plant nutrients and organic matter by the seagrass ecosystem. The high primary productivity of seagrasses supplies abundant organic carbon for bacteria to use as an energy source. Rapid oxidation of this organic matter leads to very low oxygen concentrations and hypoxic/anoxic conditions in the sediments of seagrasses. Hence, bacteria that are able to use other chemical species to oxidize the organic matter are particularly important.

Nitrate and sulfate are rapidly consumed in seagrass sediments, producing N_2 which returns to the atmosphere and a sulfide ion that either diffuses out of the sediment or combines with metal cations to form minerals in the sediment. These processes (the immobilization of dissolved inorganic nutrients, the transformation of dissolved nitrogen to atmospheric gas, etc.) are the processes that humans design waste treatment plants to accomplish. It has been estimated that it would cost $19,002 per year (1994 U.S. dollars) to build and maintain a sewage treatment plant to perform the same nutrient regulation functions as are performed by each hectare of seagrass (Costanza *et al.*, 1997). Extrapolating this areal value of the nutrient regulation processes of seagrasses to the extent of seagrasses in South Florida, the value of the nutrient regulation services provided by the seagrasses of the region is $34 billion per year (in 1994 U.S. dollars). This nutrient regulation protects coastal water quality from degradation.

Carbon Sequestration

Seagrass beds are very productive ecosystems, and they are an important net sink of CO_2 for the global carbon budget (Duarte *et al.,* 2010). The carbon sequestered in seagrass beds is stored mostly in the form of particulate organic matter in the sediments; seagrass meadows of South Florida contain, on average, about as much stored carbon per hectare as temperate forests. Their status as a net sink means that seagrasses act to buffer the global ecosystem against anthropogenic climate change. Globally, seagrass meadows tend to be autotrophic ecosystems with a mean, net community production (NCP) of 27.2 ± 5.8 mmol O_2 m^{-2} day^{-1}. The global NCP of seagrass meadows ranged (95 percent c.l. of mean values) from 20.73 to 101.39 Tg C $year^{-1}$. Extrapolating from the mean areal rates of NCP and estimates of the area of seagrass meadows in South Florida, results in an estimate of 1.2 to 3.0 Tg C $year^{-1}$ removed from the atmosphere by the seagrass ecosystems of South Florida. The global historic loss of 29 percent of the seagrass area (Waycott *et al.,* 2009) represents, therefore, a major loss of intense natural carbon sinks in the biosphere.

Attributes We Can Measure

Since 2003, nearshore benthic habitats of Biscayne Bay have been monitored by the University of Miami and NOAA's National Geodetic Survey to evaluate spatial patterns of abundance of seagrass in relationship to distance from the shore and inflow of freshwater from canals, groundwater, and overland sources (Lirman *et al.,* 2008a, 2008b). The indicators of seagrass status include seagrass and macroalgae percent cover, abundance, frequency of observation, and probability of occurrence in relationship to salinity. The data collected since 2003 show a significant relationship between salinity patterns (i.e., mean value, variability) and the seasonal abundance and spatial distribution of seagrasses.

In addition, the Miami-Dade Department of Environmental Resources Management, in partnership with the South Florida Water Management District, has conducted a benthic habitat monitoring program in Biscayne Bay since 1985. The monitoring program was initiated with 13 fixed locations throughout the bay, ten of which remain active. The program later expanded to include a rapid survey method that increased the spatial extent of the data collected to all of south Biscayne Bay. The data set from this program provides a unique long-term history of the status of seagrasses in the bay.

Where sediment depths and current are appropriate, seagrass species generally follow a pattern of zonation from west to east (*Ruppia, Halodule, Thalassia, Syringodium*) correlated with the general salinity gradient and salinity fluctuation (Lirman and Cropper, 2003). The distribution of seagrass species and other benthic flora and fauna in the western nearshore area of central and south Biscayne Bay is influenced by both canal discharges and submarine groundwater seepage (Kohout and Kolipinski, 1967; Meeder *et al.,* 1997, 1999). The presence or absence of *Thalassia* often is an indication of distinct zones where groundwater influence is substantial (*Thalassia* absent) or insignificant (*Thalassia* present).

Drivers of Change in Seagrass Beds

Pressures affecting seagrass beds in Biscayne Bay can be traced to near-field drivers that act within the region of the SEFC. Near-field drivers include damage related to boating activities, coastal construction, altered freshwater inflows, and land-based sources of pollution. While climate change and changes to ocean water chemistry are also of concern, their current impact on seagrasses in the SEFC is not as large as impacts from other drivers of change.

Coastal Development

Urban/suburban development of the SEFC poses threats to seagrass beds. It is obvious that dredging of seagrass beds to aid in access by boats and filling seagrass beds for construction lead directly to seagrass loss. However, there are other effects of increasing coastal development. Armoring of the shoreline with seawalls and docks increases the reflection of wave energy and increases erosion rates in nearshore seagrass beds. As human populations increase, nutrient loading will increase. Additional cover of impervious surfaces can increase the amount of stormwater runoff, and increased use of those surfaces by the growing population can lead to an increase in sediment and toxic chemicals in the runoff. A growing fleet of recreational vessels increases the chances of both intentional and accidental impacts of those boats on the seagrass beds.

The near-field effects of human activity in the SEFC and surrounding waters has the potential to deleteriously affect seagrasses. Increasing human population density in coastal regions has often led to eutrophication, which can reduce light available for seagrasses; eutrophication has been implicated in the loss of seagrasses from many areas of the world. Dredging and filling of coastal areas for navigation and development can directly remove potential seagrass habitat, alter hydrological conditions that lead to erosion, and cause a reduction in light available to seagrasses by increasing turbidity. Recreational and commercial use of seagrass beds can also damage them. For example, contact of the bottom by outboard motors can cause scars that can take years to recover; the cumulative impacts of such frequent events can lead to complete loss of seagrass beds from heavily-trafficked areas.

Climate Change

Since the Industrial Revolution of the early 1800s, widespread fossil fuel combustion has contributed large quantities of carbon dioxide to both atmospheric and oceanic reservoirs around the globe. Present day atmospheric CO_2 concentrations of 385 ppm represent a near 30 percent increase over pre-industrial values, with concentrations forecast to surpass 700 ppm by the end of the century (IPCC, 2007). Global sea surface temperatures are responding to these increases in CO_2 concentrations, with projected increases in sea surface temperatures of a few degrees Celsius by the end of the century (IPCC, 2007).

Changes in Ocean Water Chemistry

Roughly 30 percent of the anthropogenically-released CO_2 has been absorbed by the global oceans (Feely *et al.,* 2004), with severe consequences for the carbonate chemistry of the surface waters (Sabine *et al.,* 2004). Furthermore, CO_2-mediated increases in the abundance of H^+ ions are expected to dramatically reduce oceanic pH, with forecasts of a 0.5 unit reduction by the year 2100 (Sabine *et al.,* 2004).

Several studies have suggested that altered pCO_2 values within coastal environments may impact the functioning of both aquatic and marine plant communities (e.g., Kleypas and Yates, 2009; Martin *et al.,* 2008; Palacios and Zimmerman, 2007; Short and Neckles, 1999; Zimmerman *et al.,* 1997). External increases in CO_2 and HCO_3^- concentrations have the ability to increase seagrass production (Hall-Spencer *et al.,* 2008), leaf photosynthetic rates (Beer and Koch, 1996; Durako, 1993; Invers *et al.,* 1997; Zimmerman *et al.,* 1997), and plant reproductive output (Palacios and Zimmerman, 2007). Submerged macrophytes comprise much of the coastal benthic community around the globe and are important contributors to the carbon sink capacity of the world's oceans (Duarte *et al.,* 2010); thus, similar to declines in reef calcification, changes in oceanic pCO_2 may additionally have widespread implications for these productive and economically important ecosystems. CO_2 mediated growth responses can be rapidly constrained by the availability of other essential resources, such as water and/or nutrients (Diaz *et al.,* 1993).

Changes in Temperature and Salinity

Increasing sea surface temperatures may negatively impact seagrasses in the SEFC region. This point was illustrated by the loss of largest stands of seagrasses due to the discharge of heated water from the Turkey Point Nuclear Power Plant on the shores of Biscayne Bay in the 1960s (see review by Zieman and Wood, 1975). A rise of only 3°C caused mortality of macroalgae, and a modest 4°C rise in temperatures killed nearly all plants and animals in the seagrass bed.

In addition to the relatively direct changes in pCO_2 and temperature associated with climate change, it is anticipated that the timing and amount of rainfall and evaporation will change as well (IPCC, 2007). These changes in the freshwater budget of coastal Florida have the potential to change the salinity climate and nutrient supply in coastal seagrass beds. Species composition of seagrass beds is influenced by salinity, with increases in the amount and variability in runoff leading to a change from *Thalassia testudinum*-dominated seagrass beds to ones dominated by *Halodule wrightii* (Fourqurean *et al.*, 2003).

Mechanisms of Change in Seagrass Beds

The principal threats to seagrass beds in Biscayne Bay occur through three pathways: changes in freshwater inflow, eutrophication, and damage to seagrass beds as the direct result of human activities (Figure 2).

Freshwater inflow, from both surface and groundwater sources, are critical to maintaining the community structure and diversity in seagrass beds. The net result of water management activities has been to collect surface water flows into canals and reduce groundwater discharge into the bay. The effect has been to increase salinity throughout most of the inshore areas of the bay, away from points of canal discharge (Brown, 2003). Analysis of sediment cores from south Biscayne Bay indicates the salinities have increased on average and become less variable over the last 100-200 years (Wingard *et al.*, 2003). Channelization of the Miami River may have had a similar effect. This would have affected the competition between seagrass species and altered the zoned distribution of species with distance from the shoreline, based on salinity tolerance.

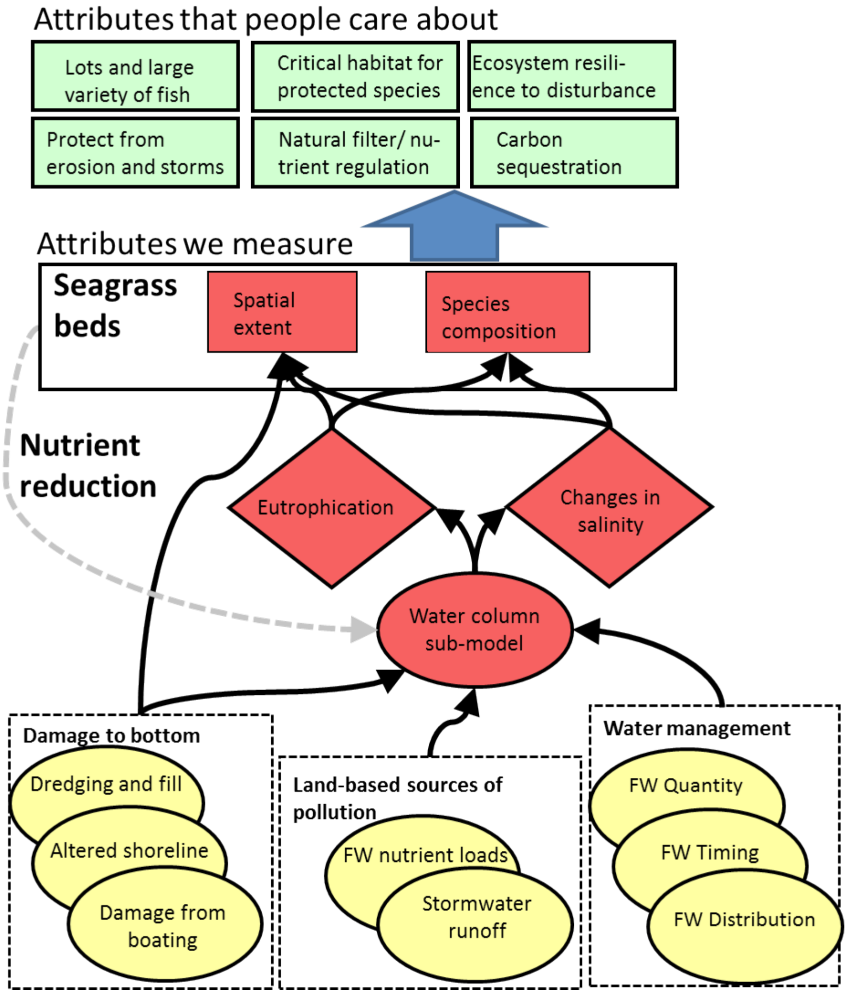


Figure 2. The seagrasses conceptual ecological submodel for the southeast Florida coast.

In general, open waters of Biscayne Bay are characterized by high dissolved oxygen concentrations, low nutrient and chlorophyll concentrations, and high water clarity. Sewage-related bacteria, trace metals, and other toxicants typically occur at low concentrations in the bay. However, water quality in a number of canals and rivers that discharge into the bay is poor in comparison to the open waters of the bay. Surface waters in some canals in South Miami-Dade County that discharge into the bay contain high levels of inorganic nitrogen. Biscayne Bay is especially vulnerable to nutrient loading by phosphorus, which is the limiting nutrient for phytoplankton growth (Brand, 1988).

Water quality in the bay can also be affected by groundwater inflows. In some areas, groundwater contains elevated levels of ammonia nitrogen from landfill leachate and nitrate-nitrogen from agriculture (DERM, 1987; Alleman, 1990; Markley *et al.,* 1990; DERM, 1993; Alleman *et al.,* 1995; Lietz, 1999; Meeder and Boyer, 2001). Submarine groundwater discharge into shallow nearshore waters is a source of elevated nutrients (Meeder *et al.,* 1997); nutrient concentrations in shallow groundwater (beneath the nearshore bay between Mowry Canal and Military Canal) are higher than found either in bay or canal waters or deep groundwater. The structure and operation of water management systems, land uses and urban and agricultural practices, and sea-level rise all affect groundwater inflow (and consequent nutrient loading) to Biscayne Bay.

Boating activities, in general, can negatively impact seagrass beds in a number of ways, including: intentional dredging for navigation and harbors; unintentional vessel groundings; increased turbidity from prop wash; nutrient loading from improper disposal of wastes; and unintentional spills of chemicals associated with boats, especially around marinas.

Fishing practices that intentionally disturb the bottom have an impact on seagrass meadows. Cockle and scallop fishing in the North Atlantic have been documented to completely remove the seagrasses that supported these economically important shellfish (Fonseca *et al.,* 1984; De Jonge and De Jong, 1992). In South Florida, the offshore waters that support the Tortugas shrimp fishery are underlain by extensive meadows of the seagrass *Halophila decipiens* (Fourqurean *et al.,* 2002). These seagrass resources are undoubtedly repeatedly disturbed by the activities of shrimp trawlers. Similarly, the bait shrimp fishery in Biscayne Bay poses a threat to seagrass meadows. Unintentional consequences of fisheries activities can also impact seagrass beds. Lobster and stone crab traps placed on the bottom can kill the seagrasses they lay on. Storms can drag these traps around the bottom, enlarging their negative effect on the seagrasses.

Seagrass Status and Trends

Concerns for the state of the seagrass beds of South Florida are well-founded. While currently the seagrass beds are nearly continuous and apparently healthy, there is cause for alarm. Despite their recognized importance, worldwide loss of seagrass beds continues at an alarming rate (Short and Wyllie-Echeverria, 1996). This loss largely has been attributed to anthropogenic inputs of sediment and nutrients. The difficulty of monitoring seagrass beds has led to obfuscation of the real extent of seagrass loss, as our best estimates of even the current global extent of this important habitat are at best within an order of magnitude (Duarte, 2002). In Florida, seagrass losses due to human activities have been reported in Pensacola Bay, St. Joseph Bay, Tampa Bay, Charlotte Harbor, the Florida Keys, Biscayne Bay, and the Indian River Lagoon (see Sargent *et al.,* 1995; Short and Wyllie-Echeverria, 1996 for reviews), but accurate estimates of the current areal extent of seagrasses even in a populated, first-world location like Florida are only recently available.

While large-scale deterioration of the seagrass beds across the entire South Florida region has yet to occur, localized cases of coastal eutrophication have led to loss of seagrasses in the SEFC marine ecosystem (Lapointe *et al.,* 1990; Tomasko and Lapointe, 1991; Lapointe and Clark, 1992; Lapointe *et al.,* 1994). The long-lived effects of the dieoff event in Florida Bay underscores the importance of healthy seagrass beds to a sustainable marine ecosystem. A poorly understood dieoff of dense stands of *T. testudinum* in Florida Bay occurred beginning in 1987. The affected area (ca. 4000 ha) was small compared to the total amount of seagrass habitat in South Florida, but the ramifications from this event were great. Turbidity in the water column and algal blooms followed the loss of seagrasses (Philips *et al.,* 1995), leading to a dieoff of sponges (Butler *et al.,* 1995), and a general decline in seagrass beds that survived the initial dieoff in an area of *ca.* 1000 km^2. Seagrass dieoff in Florida Bay is still poorly understood (Fourqurean and Robblee, 1999), and the increase in turbidity that followed the dieoff continues to effect change in western Florida Bay (Hall *et al.,* 1999; Durako *et al.,* 2002).

Topics of Scientific Debate and Uncertainty

Information is also needed to establish targets for the management of freshwater inflows from the regional water management system. How is estuarine habitat affected by changes in the quantity, timing, and distribution of freshwater inflow? What salinity gradient from interior coastal wetlands through the nearshore zone will optimize diversity and abundance of oligotrophic and mesohaline seagrass habitat? Setting these targets requires knowledge of the functional relationship between freshwater inflow and estuarine environmental parameters such as salinity and nutrient levels.

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Shoreline Habitat: Beaches

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In a nutshell:

- Beaches are the part of the coastal marine ecosystem most visited by people.
- People value beaches for the ecosystem services that they provide, including (but not limited to) flora and fauna habitat, storm protection, beach use, aesthetics, human health effects, recreation, beach-related jobs (tourism), and ocean access.
- Drivers of change include natural factors, such as the wind/wave climate, sea-level rise, submerged groundwater discharges, and upwellings, and anthropogenic factors, such as encroaching development, shoreline structures, storm water runoff, inlet discharges, and beach nourishment.
- Most beaches along the southeast Florida coast have been altered in some manner, and this must be taken into account when evaluating the status and trends in ecosystem services.

Role of Beaches—Habitat Linkages

Beaches are dynamic landscapes valued by humans because of the proximity of the ocean, the access for recreation and hunter-gatherer purposes, and the habitat beaches provide for plants and animals. Geologically, a beach is comprised of unconsolidated material affected by wave and wind forces and ocean currents. The parent material that forms the beach may be rock, sand, gravel, pebbles, cobblestones, shells, coral, or other. The term "seashore" is also commonly used for an ocean beach since some beaches front onto a river or lake.

Biotic communities of beaches provide a wide range of ecosystem services not available from any other ecosystem. Sandy beaches that remain as intact coastal ecosystems are capable of supporting both ecological processes and sustainable use by humans (Schlacher *et al.,* 2008). However, the SEFC beach and shoreline, which extends from St. Lucie Inlet to Cape Florida (Figure 1), includes some of the most densely populated coastal areas in the world. Because of this large urban footprint, the remaining natural beach habitat is limited to isolated areas, primarily in parks or other protected areas. The subtropical location of South Florida means that the beaches are influenced by both temperate and tropical oceanic environments.

Beach environments in southeast Florida are linked through the food web to the adjacent marine ecosystems, such as nearshore hardbottom, worm rock reefs, soft sediment infaunal marine communities, offshore coral reefs, estuaries,

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Figure 1. The southeast Florida region including the beaches of Martin, Palm Beach, Broward, and northern Miami-Dade counties.

and pelagic waters. This occurs primarily through feeding forays by birds and fish, detrital movement across ecosystem boundaries, macrophyte wrack (primarily Sargassum spp. from offshore and *Thalassia testudinum* from bays to the south), and by multiple habitat requirements for different life history stages of a number of organisms. Some species spend different parts of their life cycle between the beach and open-water habitats.

The ghost crab (*Ocypode quadrata*) spends its adult life in dry sand burrows on the open beach. It feeds primarily at night on clams, insects, plant material, detritus, sea turtle hatchlings, and other crabs. Ghost crabs must return to the ocean to release their eggs, which develop into larval zooplankton that remain in the ocean for a period of time. Thus, the adult ghost crab depends, in part, on food from other ecosystems, and part of its life history is spent in the pelagic marine ecosystem.

Many fishes, such as the goatfish, *Mulloidichthys* spp., feed in soft bottom areas from the nearshore to deeper offshore reef sand patches. These fishes consume food and deposit waste across ecosystem boundaries. They are prey for higher trophic level predators as they transit ecosystems.

Sea turtles also represent organisms with multiple ecosystem linkages. The adults and subadults, particularly green and hawksbill turtles, forage in nearshore hardbottom habitats. In nesting season, they deposit eggs on the beach at night then return immediately to the ocean. The eggs and hatchlings (which must travel across open beach to get into the ocean) are preyed upon by beach organisms (crabs and birds), terrestrial vertebrates (foxes, raccoons, snakes, and rats), and marine predators (fish).

Based on information from coastal scientists at the MARES SEFC workshop in March 2011, it was concluded that beaches are vulnerable to change because they are a naturally dynamic physical environment and are often the focus for intensive human use. According to Jones *et al.* (2009), the primary threats to the world's beaches include climate-change, erosion, nourishment, shoreline hardening, off-road vehicles, beach cleaning, pollution, fisheries, sand removal (mining), and introduced species, all of which apply to the beaches in the SEFC except off-road vehicles. Jones *et al.* (2009) argued that an important goal for a coastal society should be to maintain beaches in a near-pristine state since most of the value of beaches to humans comes from that natural state. In South Florida, the encroachment of urban development, recreational use, and other human activities has resulted in loss of habitat and ecosystem diversity.

Attributes People Care About that are Measured

The attributes of the beach and shoreline ecosystem that people care about include the unique oceanfront habitat, storm protection, ocean access, a continuation of the status quo for beach use, aesthetics, human health effects, recreation, and beach-related jobs for tourism (Johns *et al.*, 2013). According to the MARES Human Dimensions Ecosystem Services White Papers (Johns *et al.*, 2013; Lee *et al.*, 2013), the most important beach ecosystem services that are comprehensively measured include coastal park visitation (indicator for recreation) and dollar value of insurance claims for coastal storm damage (indicator for storm protection). In southeast Florida, coastal park visitation increased from 2009 to 2010, while the dollars spent for storm damage decreased over the same period (Lee *et al.*, 2013). The Center for Urban and Environmental Solutions at Florida Atlantic University (CUES, 2005) indicates that 44 percent of the tourists that visit a Florida beach do so in southeast Florida.

The number of jobs created by beach tourism in southeast Florida is the highest in the state, as are direct and indirect beach-related spending. Over one-third of the out-of-state Florida visitors in 2000-2003 visited a beach, and beach-oriented trips increased over the same period.

Other examples of the economic value of coastal resources for 2000-2003 include the following (CUES 2005):

- Out-of-state beach tourists spent $19.1 billion in 2003, an amount equal to 3.8 percent of the gross state product.
- Out-of-state beach tourists paid about $600 million in state sales taxes and created more than 500,000 jobs.
- Almost one-half of the more than 500,000 jobs created in Florida by beach tourism resulted from spending in southeast Florida.
- 77 percent of Florida's population lives in coastal areas.
- 80 percent of the personal income received by Florida's residents comes from coastal areas.
- 79 percent of the state's payrolls are earned in Florida's coastal areas.

Data exist for attributes of the various ecosystem services related to beaches and shorelines in southeast Florida. Categories of available beaches data and relevant references include:

- Areas of dune habitat, beach and dune fauna, and change in habitat (Defeo *et al.,* 2009; Miller *et al.,* 2010).
- Shoreline geomorphology and change (Bruun, 1962; USACE, 1996; Bush *et al.,* 2004; Jones *et al.,* 2009; Absalonsen and Dean, 2010).
- Areas of nearshore reefs and hardbottom (Perkins *et al.,* 1997; Banks *et al.,* 2008; CSA International Inc., 2009; Lindeman *et al.,* 2009).
- Water quality (Peterson and Manning, 2001; Bonilla *et al.,* 2007).
- Beach restoration (Nelson, 1993; Mota, 2011).
- Number of visitors and their economic impact (CUES, 2005).
- Values of the property on and surrounding the shoreline (Murley *et al.,* 2003).
- Economic values of the non-resident beach use (CUES, 2005; Murley *et al.,* 2005).
- Common fauna, protected species, and impacts to habitat (Johnson and Barbor, 1990; Salas *et al.,* 2006; Irlandi and Arnold, 2008; Schlacher and Lucrezi, 2009; Lucrezi *et al.,* 2009; Mota, 2011; Noriega *et al.,* 2012;),
- Other fauna including charismatic megafauna, birds, and non-natives (Schlacher *et al.,* 2008).

Drivers of Change and Pressures for Beaches and Shorelines

Drivers of change on South Florida beaches range over relatively large temporal and spatial scales, from localized overuse to global-scale sea-level rise (Defeo *et al.,* 2009; Schlacher *et al.,* 2007). *Pressures* also cause impacts at multiple temporal and spatial scales. For example, coastal engineering projects and urban development permanently impact the beach over tens of kilometers, and impacts from climate change continue for millennia over larger spatial extents. Recreation, the addition of sand for beach nourishment, and pollution impact beaches at temporal scales of weeks to years and over spatial scales of 10-100 kilometers (Defeo *et al.,* 2009).

In southeast Florida, the most widely-used environment by the residents and tourists is the beach because of its proximity to urban areas, the ease of vehicular access, and the social and cultural desirability of "hanging out" by the ocean. There are numerous federal, state, county, city, and non-government owned beachfront parks in the southeast Florida region. Most of these areas were designed to protect remaining coastal flora and fauna, provide access to the public, facilitate beach restoration, or a combination of these purposes. However, the majority of beachfront parks along the SEFC were developed to accommodate parking for public access to the beach. As a result, the development, operation, and maintenance of beach parks has resulted in significant loss of the natural aspects of the coastal landscape and increased use of the beach for active recreation.

Because beaches are popular places for people to visit, deposited waste and litter can affect the recreational and ecological uses of the beach. In severe cases, litter can cause health-related issues. In years past, beaches were commonly used for stormwater runoff disposal; though the practice continues, it is being phased out over time.

When native beach vegetation is removed, exotic species have a chance to invade. Exotic species of plants that have had an impact on beach environments in southeast Florida are *Casaurina equisetifolia*, usually called Australian Pine, and *Scaevola taccada*, also known as beach scaevola. Southeast Florida has the lowest percentage of coastline with natural vegetation in the state with only about 10 percent remaining in Broward and Miami-Dade counties (Absalonsen and Dean, 2010).

A natural beach is resilient to the frequent coastal storms that are common to the SEFC that occur several times each year. However, less frequent (every 5-30 years) hurricanes and tropical storms can significantly alter beach morphology, destroy dune vegetation, and negatively affect habitat. Southeast Florida beaches can experience major hurricanes that may cause significant changes to the form of the beach and wash away large numbers of sea turtle eggs (Figure 2). Where the energy-absorbing dune system has been replaced by urban development, even relatively minor storms cause some negative impact on the habitat and recreational uses of the beach, and the habitat loss (if any is present) can be permanent.

Most coastal communities in southeast Florida clean beaches often to remove seaweed wrack and debris. However, wrack is an important energy source to the beach ecosystem and is assimilated into the beach ecosystem via two pathways into trophic webs: decomposition and incorporation. The primary pathway is incorporation by herbivores, such as amphipods (small crustaceans with no carapace) and dipterans (two-winged insects [flies]). Subsequent predation on these grazers transfers nutrients and energy into higher trophic levels (Duong, 2008). Wrack also provides habitat for macrofauna and decomposes, remineralizing nutrients. In this manner, wrack helps to establish and support colonial dune vegetation which contributes to the storm protection function of dunes.

The shoreline of southeast Florida prior to human alteration was typical of the barrier island complexes of north and central Florida seen today. Inlets associated with river drainage (e.g., Jupiter Inlet/Loxahatchee River, New River/

Figure 2. Hatched sea turtle nest on the beach at John U. Lloyd State Park exposed by erosion from Tropical Storm Isaac (August 2012).

New River Inlet in Ft. Lauderdale) were open much of the time, depending on river flow rates. Many other inlets were ephemeral, frequently changing locations or periodically opening and closing, the dynamics of which were controlled by inland water discharge, wind patterns, and offshore storms.

As coastal development and commerce increased in southeast Florida, a need arose for stable navigational inlets of adequate water depth. The implemented solution was to install rock jetties at the desired location and dredge a channel from inland water through the barrier island or spit to the ocean. The construction of jetties interrupted the littoral sediment drift process, and down-drift beaches have been starved of their sediment supply ever since. Some of the barrier islands/spits subsequently migrated shoreward (west) until they were welded to the mainland shoreline, whose position is fixed by underlying rock formations. A prime example of a natural beach becoming beach eroded by inlet jetties is at Port Everglades in Broward County.

Based on the observed effects described above, *Drivers* and *Pressures* for South Florida beaches and shorelines were identified. *Drivers* include numerous anthropogenic factors (encroaching beach development, beach structures, beach cleaning, direct and indirect beach lighting, stormwater runoff, inlet discharges, and beach nourishment), as well as natural factors (wind/wave climate, sea-level rise, submerged groundwater discharges, and upwellings). *Pressures* on South Florida beaches and shorelines are loss of beach habitat, beach erosion/accretion, impacts to nearshore hardbottom habitat (shoreline and further out), reduced water quality, marine debris, and continued economic growth.

Beaches and Shorelines Conceptual Models

Available studies relevant to conceptual modeling of beach ecosystems were reviewed for their approach, but only a small number of existing conceptual models for beaches and shorelines were found. Most conceptual models of the shoreline have focused on beach morphology. For example, the U.S. Army Corps of Engineers developed a conceptual model for the oceanfront shoreline in New York from Fire Island Inlet to Montauk Point. This conceptual model focuses on the stresses created on shoreline habitats by alternative approaches to shoreline protection. The impact on the habitat was scored (scale of 1-3) for vegetation, invertebrates, finfish, birds, and marine mammals (USACE, 2006).

Dyson (2010) used a broker-local-tourist, place-based conceptual model of beaches as a structure for examining interactions between pollution and beach tourism. Pollution in this study included litter, construction debris, recreational boating debris, stormwater, etc. The impacts varied by category but it was concluded that beach pollution negatively affects all three categories of beach-users (broker, local, and tourist).

The Northeast Coastal and Barrier Network (NCNB) developed a conceptual model to guide a monitoring program (Figure 3; Milstead et al., 2005). The NCNB spans eight ecologically similar parks along the northeastern U.S. coast from Massachusetts to Virginia. Included are critical coastal habitat for rare and endangered species and migratory corridors for birds, sea turtles, and marine mammals. A monitoring approach was developed using conceptual ecosystem modeling to assess ecosystem agents of change, stressors and the ecosystem responses, focal resources, and key properties and processes of ecosystem integrity. Agents of change that were identified included sea-level rise, fire, biological invasions, hydrologic cycle alterations, and natural disturbance events. Stressor examples included altered hydrologic properties, altered landscape, invasive species, altered sediment, and chemical inputs. Focal resources were identified including species that are harvested, endemic, historically significant, or have protected status, as well as biological integrity. Focal resources have paramount importance for monitoring by virtue of their special protection, public appeal, or other management significance (Milstead et al., 2005).

For the southeast Florida coast, a beaches and shoreline submodel was developed by MARES, as presented in Figure 4. The state box includes beaches and shoreline attributes that people care about that are measured and the beach state variables (e.g., nearshore hardbottom and water quality). *Drivers* in the beaches submodel include wind/wave/tide, sea-level rise, upwelling, and storms, *Drivers* that are important agents of change on most beaches in Florida.

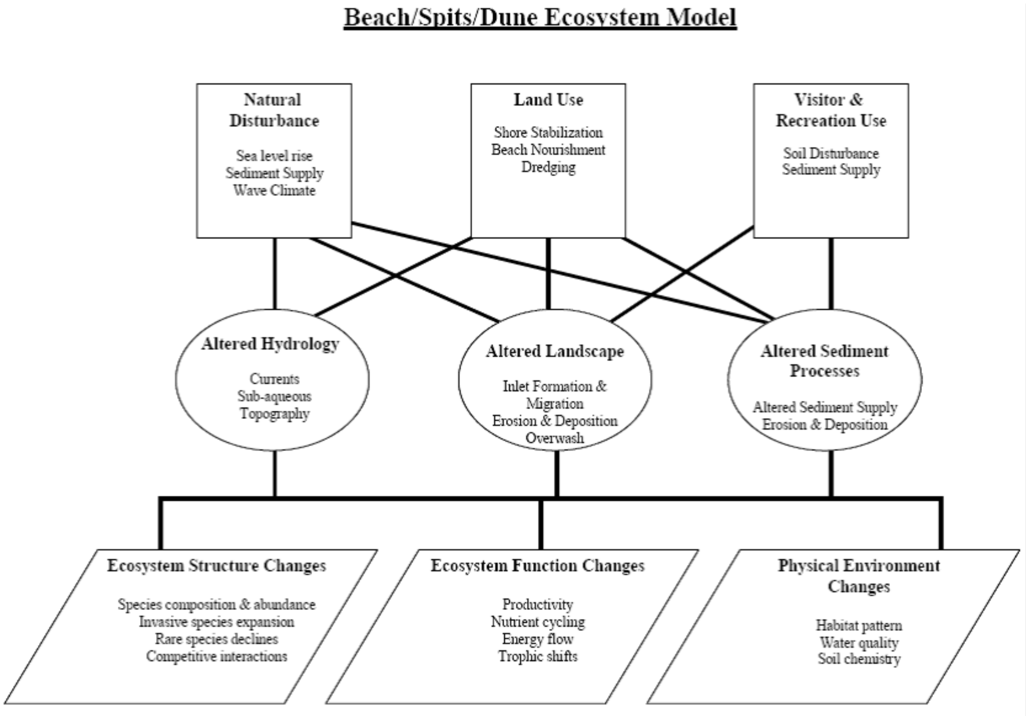

Figure 3. Conceptual ecosystem model for NCNB beach/spits/dunes (copied directly from Milstead *et al.,* 2005).

There are numerous *Pressures* in southeast Florida caused by the extent of urban development and the use of beaches, including encroaching beach development, beach lighting, mechanized beach cleaning, marine debris, beach structures, wastewater outfalls, stormwater runoff, inlet discharges, and beach nourishment. *Responses* in southeast Florida (not shown on Figure 4) include but are not limited to sea turtle conservation programs, land (beach) preservation efforts, land use plans and regulations, beach cleaning events, retro-fit and new stormwater management structures, elimination of wastewater outfalls, shielding of street lights, beach structure construction (also a pressure), and government programs to assist beach-related business efforts, and planning programs for sea-level rise.

Of particular importance as a *Driver* is the proximity of the urban development to the beach. Because a beach is a dynamic system it needs space to move, and encroachment of urban areas onto the dune and open beach areas in southeast Florida through the construction of seawalls and other permanent structures has compromised the natural function of the beach for storm protection and habitat. Beach nourishment projects are used to improve storm protection and recreational opportunities, but these projects are costly, require a great deal of time to implement, and have a large environmental impact. Improper lighting of shorefront and adjacent properties impacts sea turtle nesting and disorients hatchlings as they attempt to crawl to the ocean. The *Drivers* of change resulting from human activities that translate to *Pressures* on the ecosystem are sea-level rise and climate change. Urbanization and shoreline hardening limit the ability of the remaining beach and shoreline system to react to these drivers.

When the urban areas are located back from the shoreline, the stored sand in the dunes provides an effective and cost-efficient method of storm protection for the built environment. There is limited support for the importance of this function or the ecological value of beach habitat and, as a result, beach function as storm protection and habitat has been negatively impacted by development. When erosion or urban encroachment (or both) reduce the size of the beach and threaten storm protection or recreation, the solution is often to import beach material (beach nourishment) from elsewhere. To date, beach nourishment has not been carried out solely for the purpose of enhancing ecological value in South Florida.

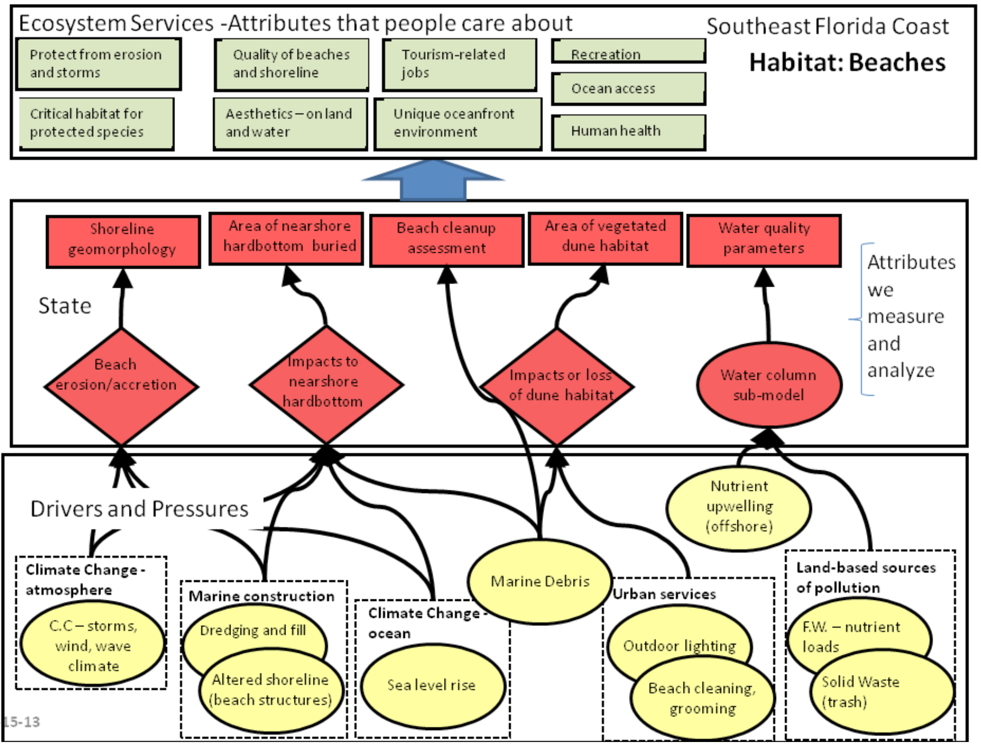

Figure 4. The beaches conceptual ecological submodel for the southeast Florida coast.

Status and Trends

The southeast Florida coastal ecosystem consists of beaches and shorelines that range from pristine to highly-impacted. Most beaches in southeast Florida have been subjected to some level of disturbance. Because of this, the discussion of status and trends for beaches and, therefore, the indicators of condition, were divided into two categories: (1) undeveloped to mostly undeveloped beaches; and (2) developed to highly developed beaches. The rationale behind this subdivision underlines the permanence of disturbance in the beach habitat. In general, undeveloped to mostly undeveloped beaches are characterized by predominately or mostly functional habitat. Beach nourishment projects must have occurred long enough in the past that the habitat is in recovery. For developed to highly developed beaches, beach nourishment has occurred relatively recently (within the past decade) and there is a high probability of a future beach nourishment project. On these beaches, the natural habitat is not likely to recover for an extended period even without any natural or human disturbance. Further details on these beach types can be found in the beaches and shorelines indicators document (Marshall *et al.,* in press).

The Southeast Florida Beach Regional Ecosystem

The southeast Florida beach ecosystem study area is comprised of several beach types including barrier islands and spits/peninsulas, as well as oceanfront areas where the Atlantic Coastal Ridge fronts directly on the Atlantic Ocean. Most beaches in the study area are experiencing long-term erosion (Table 1). The only beaches in the region that are accreting at the time that Table 1 was prepared are in Martin County. The SEFC includes many oceanfront areas that have been subjected to sand nourishment projects as a response to erosion caused by natural beach and barrier island processes, sea-level rise, and development practices.

In general, the level of development in the study area is high for all counties except Martin Country (Table 1). As a result, all counties in the study area, except Martin County, have large portions of the shore that are armored. Armoring practices include seawalls, revetments, bulkheads, groins, and boulder mounds. The existing inlets that separate the sections of beach are in locations where inlets have historically existed (e.g., Jupiter Inlet), as well as inlets

Table 1. Summary information on beaches and shorelines within the counties of the southeast Florida study area (from Bush *et al.,* 2004).

County	Ocean Shoreline (miles)	Long-Term Erosion (accretion)	Short-Term Erosion (accretion)	Beach	Level of Development	Types of Armoring
Martin	24	(4.05 ft/yr)	(2.09/ft/yr)	Yes	Low to medium	Seawalls, jetties
Palm Beach	42	0.19 ft/yr	1.17 ft/yr	Yes	High	Seawalls, groins, jetties, revetments, bulkheads
Broward	24	0.02 ft/yr	4.47 ft/yr	Yes	High	Seawalls, groins, jetties, revetments, bulkheads, boulder mounds
Miami-Dade	21	0.98 ft/yr	10.41 ft/yr	Yes	High	Seawalls, groins, jetties

that were created by dredging, often in locations where ephemeral inlets existed in the past. All of the inlets along the SEFC area are protected by jetties.

The Dynamic Physical Environment of Local Beaches

An ocean beach has several parts or zones that fluctuate in spatial extent and location with the movement of the overall beach and barrier island due to natural factors (e.g., storms) and anthropogenic alterations (e.g., hardening of shoreline). The part of the beach that may be influenced by the waves and tide is generally called the beach berm (Figure 5). A beach berm has a fore-shore or face (sloping material from the land into the water) and a wide crest called the back-shore (commonly called the open beach). Seaward of the beach berm, under water at high tide, a trough may exist beyond which longshore sand bars and other troughs may be present. Landward of the open beach, dunes of deposited beach material typically exist on natural beaches. The berm and dune forms are subjected to relatively frequent natural disturbances, less frequent storm-caused alteration, and often-permanent anthropogenic impacts.

Under natural conditions, beaches and barrier islands are dynamic environments that are influenced by climate (wind and storms), waves, and tidal action. The topography of the natural beach is shaped by the interaction of these physical processes and the mitigating effect of vegetation. Native beach plants are capable of trapping wind-blown sand to create dunes and additional habitat and can tolerate the desert-like soil conditions, burial, and the effects of direct exposure to salt spray. Human activities influence the shape of the beach and, at larger scales, the entire shoreline.

The sand composition of a natural beach in southeast Florida is a combination of quartz plus calcium carbonate materials, with the carbonate fraction increasing southward in the region. The source of the quartz sand is the Appalachian Mountains, reworked by the currents and circulation patterns of the Atlantic Ocean and the Gulf Stream, as well as local circulation patterns. Little, if any, sand on the natural beaches in the study area originated from rivers in Florida. On many beaches in the study area, the sand that exists today is sand from a borrow source via beach nourishment and may or may not have similar composition and characteristics to the native beach sand.

Higher elevation dunes form on beaches from wind and the sand-trapping process of vegetation. The above-ground portions of plants increase friction to wind. This causes deposition of aeolian sand, particularly on the fore dune. In South Florida, although the predominant wind direction is from the southeast, the greatest wind velocities come from the northeast (onshore wind). Dunes of natural sand in

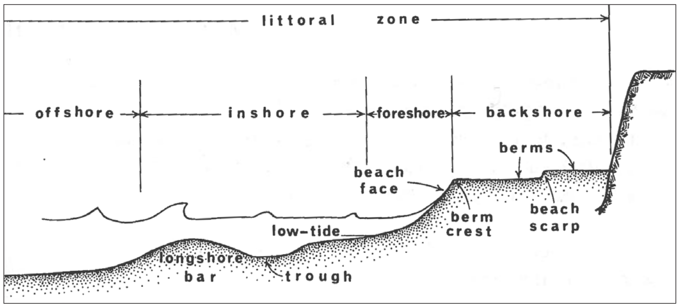

Figure 5. A typical beach profile with no anthropogenic influence (Komar, 1976).

some locations have been recorded that commonly reached heights of 25-30 ft. On developed and man-made beaches, dunes may not be present because the vegetation has been removed or destroyed. The heavy winds and turbulent seas of a hurricane can destroy dunes or alter them significantly.

Seaweed that washes ashore (wrack) may stay in the beach environment where it promotes dune formation or becomes part of terrestrial or marine food webs. During these natural processes, a diverse community of organisms, including bacteria, yeasts, fungi, nematodes, invertebrate larvae, mites, as well as macrofauna, finds shelter and engage in nutrient cycling and decomposition. If the seaweed is washed onto the berm near the dune, it can provide nutrients for dune-forming pioneer vegetation such as railroad vine (Zemke-White *et al.,* 2005). Most beaches in southeast Florida, however, are cleaned daily to remove wrack and debris, thus short-circuiting the beneficial ecological role of seaweed wrack.

Wave action moves sand in the beach system, which can result in erosion or accretion. Longshore currents transport sand over the long-term but, in the short-term, storms can alter the beach by transporting sand offshore where it is outside of the beach system (beyond depth of closure). In the vicinity of inlets, sand accretes on the updrift side (northern side in South Florida) and is eroded from the downdrift side (south side in South Florida). Most storms only erode the fore-shore or berm without over-washing, but hurricanes and winter storms (nor'easters) can accelerate erosion greatly and severely alter the beach and dune system. The beaches of southeast Florida are not as susceptible to nor'easters as the beaches of northeast Florida, due to the wave shadowing effect of the Bahamas, but they are more vulnerable to hurricanes than coastal areas in northeast Florida.

In southeast Florida the natural shoreline has been significantly altered by the dredging of inlets, construction of jetties and groins, and encroachment of urban land uses into all zones of the beach. In the most densely developed areas, the stable dune zone and the transition zone have been completely replaced by the built environment with seawalls instead of dunes and an open beach nourishment with offshore borrow sand. While beach nourishment projects are expensive, they have become commonplace activities in southeast Florida.

Absalonsen and Dean (2010) studied shoreline change in southeast Florida since the late 1800s. Their data reflect the significant impact that navigational inlets have on the littoral transport system. In general, there is a prograding of the shoreline position north of navigational inlets and a sharp erosion signal to the south. Variation in shoreline position is greater at these locations compared to the more stable beaches between inlets.

Climate

The beaches of southeast Florida are highly influenced by the variability of climate factors. The climate of southeast Florida is classified in the Köppen Climate Classification System as tropical savanna, characterized by a pronounced dry season (Trewartha, 1968). Air temperature averages 19.0°C in the winter and 28.2°C in summer, with an overall average of 24°C. Water temperatures are moderated by the proximity of the northward flowing Florida Current, an arm of the Gulf Stream passing through the Straits of Florida. The minimum water temperature measured offshore Broward County during a 3-year period (2001-2003) was 18.3°C and the maximum was 30.5°C (Banks *et al.,* 2008).

During the dry season (November–March), Florida experiences the passage of mid-latitude, synoptic-scale cold fronts (Hodanish *et al.,* 1997) which bring strong winds from the northeast. These nor'easters usually last for 2-3 days. These fronts may have a significant impact on the beach ecosystem by increasing southward sediment transport (littoral transport), offshore loses of coarse beach sediment (with some burial of nearshore hardbottom), and shoreward aeolian transport of fine sediments which contribute to increases in dune elevation. Strong winds also generate waves which can cause a flattening of the beach profile and may form scarps on the beach berm and erosion of dunes.

In the wet season (late spring to early fall, June–September), differential heating generates mesoscale fronts, creating sea breezes. Convergence of these moisture-laden sea breezes, developing from the different water bodies (Atlantic Ocean, Gulf of Mexico, and Lake Okeechobee), coupled with high humidity in the Everglades, can result in a low-pressure trough developing across the Florida peninsula. This leads to intense thunderstorm activity, which moves from inland to the coasts, delivering large amounts of freshwater to the coastal shelf. South Florida receives 70 percent of its annual rainfall during these months. Trewartha (1968) referred to the daily sea breeze circulation as a "diurnal monsoon". The typical wind direction during most of the southeast Florida wet season is from the southeast (tropical). During these times, winds tend to be relatively light and cause little beach erosion.

From June through November, Florida is a prime landfall target for tropical cyclones, although storms have been documented as early as March and as late as December. Hurricanes and tropical storms affect the beach ecosystems similar to winter storms, except alteration of the physical environment is magnified because of stronger winds with the added impact of high water levels caused by storm surge. Because winds in a hurricane shift in direction as the storm passes, longshore sediment transport direction can shift. The numbers of direct hits of hurricanes (strength based on the Saffir-Simpson scale) affecting southeast Florida in the 100 years from 1899-1998 (Neumann *et al.,* 1999) are:

- Category 1 (winds of 119–153 km/hr) – 5
- Category 2 (winds of 154–177 km/hr) – 10
- Category 3 (winds of 178–209 km/hr) – 7
- Category 4 (winds of 210–249 km/hr) – 4
- Category 5 (winds > 249 km/hr) – 1

The number of tropical storms or hurricanes passing within a 50-mile radius of Palm Beach, Broward, and Miami-Dade counties (a single storm may affect more than one county) are presented in Table 2.

Waves and Tides

Long-period swells result in increased sediment suspension and turbidity in nearshore waters. Hanes and Dompe (1995) measured turbidity concurrently with waves and currents in situ at depths of 5 m and 10 m offshore Hollywood, Florida (Broward County) from January 1990 to April 1992. They found a significant correlation between wave height and turbidity. In addition, there was a threshold wave height (0.6 m), below which waves do not materially influence turbidity.

In winter, low-pressure systems form on the Atlantic Ocean coast of the U.S. Short-period, wind-driven waves develop near the center of these lows. As these seas move away from the center of low pressure, they can develop into long-period swells, locally known as "ground swells" that may affect southeast Florida. The wave climate of southeast Florida is influenced by the shadowing effect of the Bahamas and, to a lesser extent, Cuba. In the northern part of the southeast Florida region, swells from the north are of relatively high energy since they are not influenced by the shallow Bahamas Banks. Broward and Miami-Dade counties are less affected

Table 2. Storm occurrences for southeast Florida (USACE, 1996).

	Palm Beach County		Broward County		Miami-Dade County	
Period	Hurricanes	Tropical Storms	Hurricanes	Tropical Storms	Hurricanes	Tropical Storms
1871–1880	3	0	1	0	0	0
1881–1890	2	2	1	2	2	2
1891–1900	0	2	0	1	1	1
1901–1910	2	4	2	3	3	2
1911–1920	0	0	0	0	0	1
1921–1930	3	1	4	0	3	0
1931–1940	3	0	2	1	1	2
1941–1950	5	1	4	1	5	1
1951–1960	0	2	0	2	0	2
1961–1970	2	0	2	0	2	0
1971–1980	1	1	1	1	0	1
1981–1990	0	2	0	2	1	1
1991–2000	0	2	1	0	1	1
2001–2006	3	0	1	0	0	1

by this wave energy because of the shadowing effect of the Bahamas Banks.

Tides in the region are semi-diurnal with amplitudes of approximately 0.8 m. Tidal forces influence coastal circulation near navigation inlets. Nine navigational inlets, approximately 16 km apart, are maintained in southeast Florida. At the southern extent of the region, tidal passes allow exchange of water from Biscayne Bay onto the coastal shelf. The relative contribution of the inlets to coastal circulation can be estimated by comparing inlet tidal prisms (volume of water exchanged in the estuary between high and low tide). Coastal circulation is affected by the tidal prism, inlet dimensions, shelf width at the inlets, offshore distance of the Florida Current, tidal plume constituents, and salinity. The salinity of the plumes discharging from the inlets is significantly different in the wet season (June–September) compared the dry season (October–May).

Ecological Communities and Characteristic Species

Natural beaches in the Southeast Florida study area have or had vegetation that is (was) somewhat similar throughout the extent of the study area, although tropical species are a larger portion of the native ecosystem in the southern extremes and subtropical beach vegetation may be seen in the northern part of the study area on natural beaches (Johnson and Barbour, 1990). Beach vegetation within the study area typically occurs in the berm and back dune areas that are generally parallel to the shoreline and oriented in a north-south direction. The transition (ecotone) from temperate to tropical canopy trees occurs in the northern reach of the study area. North of the study area, the tropical species, when present, prefer the calcareous substrate. There are a number of animals that depend upon the beach habitat for at least part of their life cycle, including sea turtles, numerous birds, and rodents.

Based on plant lists by Johnson and Barbour (1990), beach and fore dune representative species in the study area include sea oats (*Uniola paniculata*), sea purslane (*Sesuvium portulacastrum*, *Distichlis spicata*) beach dropseed (*Sporobolus virginicus*), Mexican beach peanut (*Okenia hypogaea*), Remirea maritima, railroad vine (*Ipomoae pes-caprae*), seashore paspalum (*Paspalum distichum*), sea lavender (*Argusia* sp.), beach sunflower (*Helianthus debilis*), beach berry (*Scaevola plumier*), and bay cedar (*Suriana maritima*). Because the barrier island and non-barrier beaches of southeast Florida are narrow, the transitional zone may be dominated by woody species of plants including sea grape (*Cocoloba uvifera*), Serenoa repens, Sable palmetto, *Dalbergia ecastophyllum*, Spanish bayonet (*Yucca aloifolia*), agave (*Agave decipiens*), and prickly pear (*Opuntia stricta*). The native stable dune zone in southeast Florida contains primarily woody shrubs and canopy trees dominated by tropical species, although the northernmost reaches of the study area contain subtropical species. Representative native stable dune canopy plants include *Eugenia foetida, Aradis escallonioides, Bursera simaruba, Eugenia axillaris, Metopium toxiferum, Cocothrinax argentata, Mastichodendron foetidissimum, Zanthoxylum fagara, Amyris elemifera, Krugiodendron ferreum, Nectandra coriacea, Casuarina equisetifolia* (exotic, invasive), *Pithecellobium keyensis, Chrysobalanus icaco,* and *Rivina humilis*. Johnson and Barbour (1990) indicate that about ten endemic plant species were found in the study area, although the number may be decreasing due to the intensity of development and the loss of tree canopy habitat.

Sea turtles spend most of their life in the ocean but females return to the beach to deposit eggs in nests. From May to September (earlier for leatherbacks), female sea turtles emerge from the ocean mostly at night onto the beach to lay a clutch of eggs that will hatch in about 60 days. The hatchlings then leave the nest and travel across the open beach to enter the ocean and swim to offshore nursery areas. The beaches of southeast Florida are globally important beaches for sea turtle nesting (Witherington *et al.,* 2009). In the vicinity of inlets, sea turtles can also be found in the estuary.

The sea turtle species that use southeast Florida beaches for reproduction are, in order of presence (common to rare): loggerhead (*Caretta caretta*), green (*Chelonia mydas*), leatherback (*Dermochelys coriacea*), hawksbill (*Eretmochelys imbricata*), and Kemp's ridley (*Lepidochelys kempii*). According to the U.S. Fish and Wildlife Service, there are about 35 leatherback (endangered) nests in all of Florida each year, over 10,000 loggerhead nests (threatened), and about 200-1100 green turtle nests (endangered). There are five subpopulations of loggerheads worldwide, and the southeast Florida subpopulation is genetically distinct from the loggerhead subpopulation in north Florida and other sub-populations. The only nesting regions in the world with over 10,000 loggerhead nests a year are southeast Florida and Masirah (Oman). The southeast Florida subpopulation experienced population increases for many years, although current data indicate that this trend may have slowed. The Florida green turtle nesting aggregation is recognized as a regionally significant colony (http://www.fws.gov/northflorida/SeaTurtles/seaturtle-info.htm).

Data are collected by Florida Fish and Wildlife Conservation Commission (FWC) for the number of sea turtle nests that are laid in the southeast Florida region. These data are summarized by year and by county in Table 3 for 2006-2010. Year 2010 was a year of high nest numbers for both loggerhead and green sea turtles. By comparison, 2006 was a year of low or reduced nesting for all three species (Witherington *et al.,* 2009).

For some birds the beaches of southeast Florida are important nesting sites. For other species, the beach is used as a wintering ground. Johnson and Barbour (1990) indicate that there are 13 bird species in Florida that use the beach for nesting, usually from April to August, with no detail on southeast Florida. Examples of wintering species in southeast Florida may include sanderlings (*Calidris alba*), western sandpiper (*C. mauri*), dunlin (*C. alpine*), short-billed dowitcher (*Limnodromus griseus*), red knot (*Calidris canutus*), black-bellied plover (*Pluvialis squatarola*), and willet (*Castrophorus semipalmatus*).

Small rodents are also an important component of the natural beach habitat. Barrier island rodent populations are distinct from populations of mainland subspecies, and subspecies in other parts of Florida are distinct from those in southeast Florida. Little detail on the subspecies of rodents in southeast Florida was found.

The interstitial spaces of the sand on a beach near the waterline support a relatively diverse infauna that experience cyclic changes of water due to diurnal tide cycles and seasonal variation in the nearshore marine areas. Chemical stratification of the sand can result in varying environmental conditions over short vertical distances. Infaunae are represented by fungi, algae, bacteria, metazoans, and protozoans (McLachlan, 1983). In the swash zone of southeast Florida where wave action and tides dominate, the physical processes, coquina clams (*Donax* spp.), and mole crabs (*Emerita talpoida*) are commonly present (Wade, 1967). On an undisturbed open beach, the most obvious organism is the ghost crab (*Ocypode quadrata*).

Table 3. Marine turtle nesting data by year and by county (FWC data, http://myfwc.com/research/wildlife/sea-turtles/nesting/beach-survey-totals/).

Species	County	2006	2007	2008	2009	2010
Loggerhead	Martin	5,532	5,210	7,356	6,643	9,120
	Palm Beach	11,196	10,559	12,704	11,565	15,775
	Broward	1,740	1,593	1,929	1,808	2,283
	Miami-Dade	302	295	323	358	352
	Total	18,770	17,657	22,312	20,374	27,530
Green	Martin	579	1,307	1,111	679	1,591
	Palm Beach	1,324	3,389	2,272	1,263	3,378
	Broward	138	233	276	71	268
	Miami-Dade	0	20	0	12	13
	Total	2,041	4,949	3,659	2,025	5,250
Leatherback	Martin	205	494	274	663	561
	Palm Beach	225	490	243	615	368
	Broward	15	41	14	45	14
	Miami-Dade	3	8	10	5	2
	Total	448	1,033	541	1,328	945

Nearshore hardbottom areas are found in proximity seaward of most beaches in southeast Florida, particularly south of Hillsboro Inlet in Broward County. Much of the nearshore hardbottom substrate in the northern areas of the region was created by sabellarid polychaete worms. Nearshore hardbottom substrate in the central region is primarily Anastasia Formation (coquina), while south of Port Everglades (Broward County) carbonate grainstones dominate. Nearshore hardbottom may be ephemeral due to offshore sand movement from the beach system during high wave energy events. This ephemeral nature may be greatly enhanced by sediment inputs from beach nourishment projects. CSA International, Inc. (2009) provides a review of the nearshore hardbottom communities in southeast Florida.

Microbial Contamination of Water and Sand

Water quality of southeast Florida's beaches is routinely monitored for fecal indicator bacteria. If standards are exceeded, the beach is closed to bathers. Beach sand, however, is not monitored, yet sands and sediments provide habitat where fecal bacteria may persist and grow in some cases (Halliday and Gast, 2011). Bonilla *et al.* (2007) found that the length of time a person spent in wet sand and time spent in the water were correlated with increased gastrointestinal illness in southeast Florida. Gull feces were responsible for some of the elevated levels, yet could not account for the overall higher microbial concentrations in sands.

Discussion and Topics of Scientific Debate and Uncertainty

Even though there is information on the effect of natural and human disturbances of the beaches and shore habitats from site-specific studies and on-going monitoring programs, there is also scientific debate and uncertainty regarding the damaging effects of some activities. Data collection and discussion continue on the impacts of beach nourishment on nearshore hardbottom, sea turtle nesting, and shore fishing, as well as sea-level rise and beach erosion.

Burial of nearshore hardbottom can occur during nourishment of eroded beaches or afterwards, when the fill profile is adjusting to the wave climate (fill equilibration). This habitat loss has to be mitigated under permit requirements, but questions remain regarding successful mitigation strategies, prediction of the amount of nearshore hardbottom burial, and subsequent amount of necessary mitigation. Determining successful mitigation requires a detailed knowledge of the nearshore ecosystem, including natural variation across space and time. Often, long term ecological data are lacking. Predicting the effects of burial is difficult because of the complexity of nearshore sediment dynamics and a paucity of studies to support the modeling that has been done. Mitigation requirements are based on time of recovery of damage, mitigation community development trajectories, and quantification of services provided by both. Input data for these requirements are often based on hypothetical assumptions.

The effect of beach nourishment projects on sea turtle nesting is manifested by reduction in nest densities and/or nesting success (the percentage of crawls resulting in a nest). This occurs for the first few seasons following construction. This has been thought to be caused by escarpments and increased sediment compaction. In 2004, however, the Florida Department of Environmental Protection proposed that beach profiles might have an impact on nest success. Earnest *et al.* (2011) proposed a "turtle-friendly" design profile based on review of previous monitoring studies. Additionally, Mota (2011) found that hatchling fitness is affected by oxygen and carbon dioxide fluxes in nests. Beach nourishment can increase the calcium carbonate content of sand which increases compaction, decreasing circulation of atmospheric gases.

Shore or surf fishing is a popular activity in southeast Florida. The most commonly targeted fish is the pompano whose preferred food is the sand flea or mole crab (*Emerita talpoida*). Sand fleas are captured in the intertidal zone so disruptions from beach nourishment could have detrimental effects on the populations. Surf fishing is a recreational activity and the impact of beach nourishment on the fishery is currently not known.

Beach erosion (shoreline retreat) from sea-level rise can be quantified by the Bruun Rule (Bruun, 1962). Areas hemmed in by urban development may not be able to adapt to sea-level rise, and erosion is expected to increase with loss of beach habitat.

Methods to hold sand on beaches, such as artificial seaweed, littoral "speed bumps," beach dewatering, structures (groins, breakwaters), and amino acid applications have not been successful to date and some have caused increased erosion impacts downdrift. The future approach that offers the least environmental impact is small scale (small volume), frequent beach nourishment, using upland or foreign sand sources. However, the most cost-effective method of holding sand on southeast Florida beaches is to protect the natural beach physical environment and habitat. Unfortunately that is now only possible in limited beach locations.

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Shoreline Habitat: Mangroves

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In a nutshell:

- The mangrove forests along the southeast Florida coast provide critical nursery and foraging habitat for numerous marine species of economic value; sequester carbon, as well as export organic materials that support coral reef and seagrass food webs; and are critical nesting and foraging habitat for marine water birds.
- People care about mangroves because they provide excellent fishing habitat; stabilize shorelines and provide a buffer against storm surges; are critical habitat to protected and charismatic species; and provide aesthetic, recreational, and tourism value.
- Mangrove habitat has been destroyed largely by urbanization and development of the southeast Florida coastline. The large-scale loss of mangroves has all but ceased due to laws protecting wetlands; however, these laws are continuously under threat of being relaxed.
- Climate change is the largest global threat to mangroves of the southeast Florida coast. Sea-level rise, increased frequency of tropical storms, and increased variability in temperature can result in large-scale changes in spatial extent and community structure of these forests.

Description of Resource

Prior to urbanization, there were 95,000 hectares of mangrove forests along the SEFC and Florida Keys (Figure 1) (Coastal Coordinating Council, 1974). Ecosystem Services provided by these mangrove forests include nursery habitat for numerous fishery species of economic importance and critical foraging habitat for adults of some of these same species (Odum et al., 1982; Lewis et al., 1985; Faunce and Serafy, 2006). They provide foraging and nesting habitat for South Florida's ubiquitous fish-eating birds (Odum et al., 1982), as well as nesting and stopover habitat for resident and migratory passerine bird species (Odum et al., 1982). They are highly effective at sequestering carbon dioxide and nutrients, and they protect shorelines from erosion and storm surges (Odum and McIvor, 1990). Local, regional, and global stressors, both natural and anthropogenic, may result in loss of this habitat in the SEFC. The processes by which these losses occur and why they should be minimized are defined in the ICEM (Figure 2).

There are three species of mangroves along the SEFC: red (*Rhizophora mangle*), black (*Avicennia germanans*), and white (*Laguncularia recemosa*). Buttonwood (*Conocarpus erectus*), a mangrove associate, is also common in mangrove forests in southern Florida. Tidal forces, climatic conditions, and soil type result in these species forming six different forest types: overwash, fringe, riverine, basin, hammock, and scrub forests (Lugo and Snedaker, 1974). The arrangement of the species within forest type determines the biota that occur within the mangrove forests (Lugo and Snedaker, 1974). Epiphytes and sessile invertebrates frequently grow on specialized root adaptations of mangroves (prop roots and pneumatephores) and these, plus the mangrove leaf litter, are the basis of mangrove food webs (Odum and Heald, 1975). Odum *et al.* (1982) reported that 220 species of fish, 21 reptiles, three amphibians, 18 mammals, and 181 birds utilize the mangroves of southern Florida.

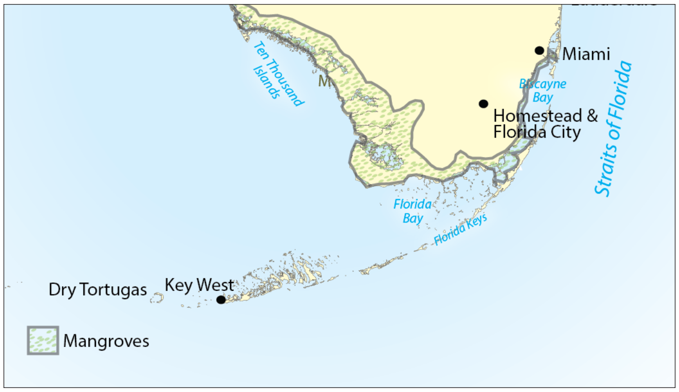

Figure 1. Mangrove forests along the southeast Florida coast and Florida Keys.

Role of the Mangroves in the Ecosystem

Mangrove forests provide critical nesting habitat for water birds (Kushlan and Frohring, 1985; Ogden, 1994) and nursery habitat for fishery species (Ashton and Eggleston, 2008; Comp and Seaman, 1985; Lewis *et al.,* 1985; Manson *et al.,* 2005). In addition, these wetlands enhance the fish biomass on nearby seagrass beds (Manson *et al.,* 2005; Thayer and Chester, 1989) and corals, and other reef-building invertebrates have been found to assimilate mangrove organic material (Granek *et al.,* 2009). The mangroves of the SEFC are highly productive in small demersal fishes and invertebrates (Heald *et al.,* 1984; Lorenz, 1999) that, during relatively low water periods, become highly concentrated and exploited by water bird species (Lorenz *et al.,* 2002; Odum *et al.,* 1982; Ogden, 1994; Powell, 1987) and game fish (Odum *et al.,* 1982; Odum and Heald, 1975). These wetlands also sequester nutrients and act as a wastewater filter (Ewel *et al.,* 1998), thereby playing a role in water quality, and they are sources for export of organic material into coastal waters (Lugo and Snedaker, 1974; Odum and Heald, 1975; Twilley, 1985, 1988; Nixon, 1980).

Attributes People Care About

The mangroves of the SEFC provide critical *Ecosystem Services* to the entire southeast coastal ecosystem including:

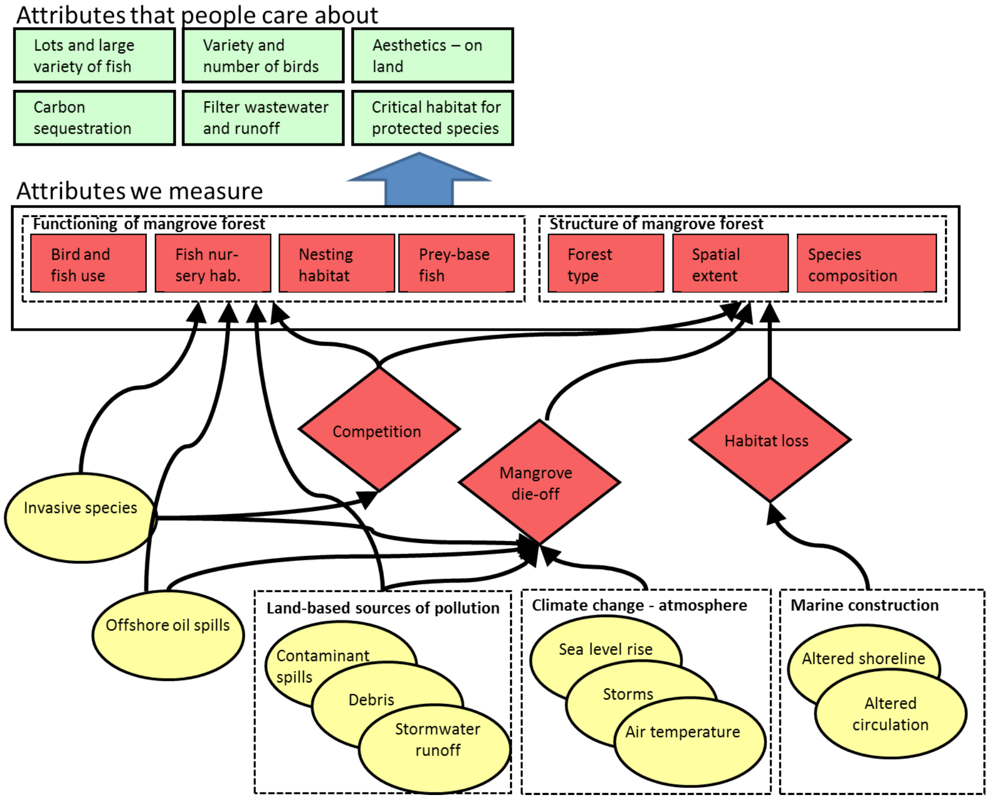

Figure 2. The mangroves conceptual ecological submodel for the southeast Florida coast.

- Coastline protection and stabilization
- Bird habitat—foraging, nesting, and migratory
- Fish habitat—nursery and feeding
- Aesthetics
- Natural filter for wastewater and storm runoff
- Carbon sequestration
- Habitat for protected and keystone species
- Source of dissolved organic matter
- Wood products
- Honey production

Coastline Protection and Stabilization

Property owners along the SEFC benefit from the protection that mangrove shorelines provide during tropical storms. These forests buffer wind speeds and attenuate storm surges, thereby reducing the effects of these forces on developed properties (Barbier *et al.,* 2011; Ewel *et al.,* 1998). Mangrove-lined creeks also provide safe anchorages to boats during storms.

Bird Habitat

Bird watching is one of the fastest growing past times in the U.S. (Carver, 2009), and advertisements in "birding" literature are used by the Monroe County Tourist Development Council to attract bird watchers to the SEFC (personal observation). The presence of a diverse community of birds, including those that are dependant on mangrove forests, provides high levels of satisfaction to vacationing bird watchers, as well as the hoteliers and restaurateurs that cater to this generally affluent group of tourists (Carver, 2009). Furthermore, even tourists who have no inclination toward bird watching have their visits enhanced by seeing such common species as brown pelicans, osprey, eagles, herons, ibis, and spoonbills, thereby leading to higher visitor satisfaction.

Fish Habitat

As stated above, mangrove root habitat provides nursery habitat for economically valuable juvenile fish and shellfish and provides foraging habitat for game species. Harding (2005) estimated that in 2005 retail sales associated with saltwater recreational fishing in Monroe and Miami-Dade counties totaled $408.7 million and supported more than 7,200 jobs. Backcountry fishers target game species such as mangrove snapper, seatrout, redfish, tarpon, and snook from among the mangrove prop roots and adjacent waters, while offshore fishers target adult grouper and snapper species that spent part of their early life cycle in the mangrove forest (Lewis *et al.,* 1985). Commercial fishers also benefit from mangroves because the three species with the largest dockside landings value in the SEFC (pink shrimp, Caribbean spiny lobster, and stone crabs) also spend portions of their juvenile life stages in mangrove forests (Lewis *et al.,* 1985).

Aesthetic Value

Leeworthy and Wiley (1996) surveyed residents and visitors of the SEFC and determined that wildlife viewing/nature study was a top activity. The aesthetic value of myriad mangrove islands and meandering, mangrove-lined creeks certainly adds to the value of these activities.

Wastewater/Storm Water Filtration

Mangrove forests act as sinks for both nitrogen and phosphorus, taking in these nutrients as water flows through the forest (Odum *et al.,* 1982). Wastewater and stormwater are rich in these nutrients, which can be damaging to coral reefs and other ecosystems (see water quality and coral-hard bottom submodels). The presence of mangroves adjacent to developed areas of the SEFC reduces the amount of nutrients reaching the reefs by filtering runoff through the forests. Furthermore, mangroves have been demonstrated to remove and sequester heavy metals (Foroughbakhch *et al.,* 2008) that are a component of stormwater runoff and can be damaging if they enter the various food webs of the SEFC.

Carbon Sequestration

Mangrove forests store massive amounts of carbon (Howe *et al.,* 2009). The loss of mangrove forests not only releases the stored carbon but also prevents further sequestration of carbon. By removing CO_2 from the atmosphere through photosynthesis and thus sequestering this recognized greenhouse gas, mangroves provide a valuable service to human society.

Critical Habitat for Protected and Keystone Species

Manatee, small-toothed sawfish, goliath grouper, bottlenose dolphin, white-crowned pigeon, reddish egret, Lower Keys striped mud turtle, key deer, American crocodile, bald eagle, osprey, brown pelican, and mangrove cuckoo are examples of protected species that rely on or frequent mangrove habitats along the SEFC. Losing more mangrove habitat could further endanger these species, lowering biodiversity and also making the SEFC less attractive as a place for people to observe rare species of animals. In particular, many snorkelers will visit mangrove habitats in search of charismatic megafauna such as manatees and sharks.

Export of Organic Material to Other Ecosystems

Although mangroves are a net sink for carbon, they do export organic matter to other marine systems (Odum *et al.*, 1982). Granek *et al.* (2009) demonstrated that filter feeders such as sponges, bivalves, and corals consume and assimilate mangrove-based organic matter when in proximity to mangrove forests.

Wood Products

Today, there is no commercial harvesting of mangroves in southern Florida, but there are artisanal uses of mangroves for wood working, art works, and cooking wood (personal observation). Mangroves are harvested in many parts of the world to be used in wood products (Odum *et al.,* 1982). Historically, in southern Florida (including the SEFC) buttonwood was harvested for use in charcoal production, and red mangrove bark was harvested to manufacture tannic acid (Tebeau, 1968).

Honey Production

The Florida Agricultural Statistics Service reports that Florida was the fourth largest honey-producing state in the U.S. in 2008, with an estimated value of $15.4 million. Black mangrove honey is of a very high quality such that the tree is sometimes referred to as the “honey mangrove” (Florida Fish and Wildlife Research Institute, 2006). Apiarists along the SEFC target blossoming black mangrove stands to house their hives and market black mangrove honey (personal observation).

Attributes We Can Measure

To assess the health of the SEFC mangrove forests and determine how they are responding to sea-level rise, climate change, and land use pressures, researchers can measure key attributes of the system.

- Mangrove forest spatial extent, forest type, and tree species composition
- Prey base production
- Wading bird and game fish use
- Fish nursery capacity
- Changes in bird nesting habitat

Mangrove Forest Spatial Extent, Forest Type, and Species Composition

Mangrove forests of the SEFC were destroyed in large numbers during the development boom from the late 1950s to the early 1980s (Strong and Bancroft, 1994). Currently, mangrove habitats are protected along the SEFC, and loss of spatial extent is largely inconsequential although there is still some loss. It is, however, still important to monitor spatial extent, forest type, and species composition to determine the affects of illegal clearing, tropical storms, invasive species, and climate change. Historically, mangrove spatial extent and forest type were quantified using aerial photographs taken by systematic flights from a fixed-wing aircraft (Eglar, 1952). Estimates of cover were then made using transparent grid paper and the percent of habitat estimated (Eglar, 1952). In more modern times, the aerial photographs were digitized using computer global information system (GIS) programs (Strong and Bancroft, 1994). Currently, satellite imagery can be directly analyzed using state-of-the-art GIS software to acquire highly-accurate estimates of spatial extant and forest type defined (Sabrato and Kushwaha, 2011; Wu *et al.*, 2006). Species composition is generally monitored using standardized transect surveys (Fourqurean *et al.,* 2010); however, aerial reconnaissance using light detection and ranging (LiDAR) techniques has shown promising results in other forest types (Jones *et al.,* 2010).

Fish and Bird Use of Mangrove Forest

Faunal studies along the SEFC have largely focused on bird and fish use. Faunal surveys of indicator species or species composition can provide vital information regarding the health of mangrove ecosystems (Bortone, 2005). Because animals respond more rapidly to perturbations than trees, these surveys can reveal the affects of perturbation before permanent damage is done (Bortone, 2005).

For example, Bancroft and Bowman (1994) used white-crowned pigeons as an indicator species to demonstrate the importance of mangroves to the spread of seeds in nearby deciduous forests. They preformed nest surveys and the number of birds entering and leaving a nesting colony to determine the number and spatial extent of pigeon use of mangroves (Strong *et al.,* 1994). Lott *et al.* (2006) used species composition to determine the importance of forests along the SEFC to migrating species by capturing birds in nets and through visual observations. Lorenz *et al.* (2002) made repeated visits to nesting colonies of roseate spoonbills to estimate nesting success.

Fish use of SEFC mangroves has also been performed to gauge the health of the ecosystem and the importance of mangroves. Lorenz and Serafy (2006) used a fish trapping method of the demersal prey-based fish community to demonstrate the deleterious affects of fluctuating salinity on prey abundance. Mark and recapture techniques, visual censuses, video recordings, and acoustic tagging have also been used to track fish movements from mangrove habitats to nearby seagrass and coral reef habitats, thereby demonstrating the importance of mangroves (Farmer and Ault, 2011; Faunce *et al.,* 2004; Meynecke *et al.,* 2008; Murchie *et al.,* 2010; Russell and McDougall, 2005; Verweij and Nagelkerken, 2007). These studies provide valuable information regarding the health of mangrove forests, as well as the importance of mangroves to what humans desire in the marine environs of the SEFC.

Drivers of Change

The coastal transition zone represents a region where sustainability is dependent upon a balance of forces, including climate, tidal fluctuation, runoff of freshwater and terrestrial nutrients, substrate, and wave energy (Odum and McIvor, 1990). The primary driver of change that will affect the SEFC mangroves in the coming decades and centuries is global climate change (Davis *et al.,* 2005); however, contaminant spills, invasive species, and urbanization all pose significant threats. These pressures, with the exception of marine debris, can result in changes in forest type, tree species composition, or the loss of mangrove forests entirely. Invasive plants, through competition with mangrove trees, can change the species composition and the type of forest or can displace mangroves entirely. Invasive animals, contaminant spills, freezes, and hurricanes can result in mangrove kills. After the trees are killed, they can be replaced by different species (Craighead, 1971), different forest types (Odum *et al.,* 1982), or replaced by non-mangrove habitat (Craighead, 1971; Wanless *et al.,* 1994), resulting in overall loss of mangrove forest spatial extent. The pressures listed previously, with the exception of marine debris, can result in changes in forest type, tree species composition, or the loss of mangrove forests entirely.

Description of Pressures

Exogenous Contaminants

Petroleum oil spills are of particular concern for mangrove ecosystems since the oil can spread over a wide area, resulting in the loss of entire forests (Duke *et al.,* 1997). The Straights of Florida and the Gulf Stream are major shipping lanes, and an oil spill from a large tanker could destroy large areas of mangrove forests (Jackson *et al.,* 1989; Duke *et al.,* 1997). A drilling accident close to the SEFC, as might occur with the advent of oil exploration in Cuban territorial waters (Gold, 2011) or if Florida's coastal waters are open to oil exploration and extraction, could result in the same. Oil extraction as far away as the northern Gulf of Mexico can also result in damage to the SEFC if the oil is entrained in the Gulf's Loop Current and carried south to the Straights of Florida (Sturges *et al.,* 2005). Such was the fear in the 2010 Deepwater Horizon/British Petroleum oil rig explosion (Thibodeaux *et al.,* 2011). Stormwater runoff may contain petroleum products or other contaminants that may also be injurious to mangrove trees in urbanized areas of the SEFC. Discarded human refuse (e.g., litter, discarded fishing gear) can become trapped by mangrove root specialization and cause damage by capturing and killing animals and by reducing the aesthetic value for humans.

Global Climate Change

Wanless *et al.* (1994) estimated sea-level rise along the SEFC to be 20-40 cm per century and that mangroves could accrete soils up to 30 cm per century. The IPCC (2007) predicted that future sea-level rise will be between 20-60 cm per century. These estimates suggest that mangrove accretion may not keep pace with sea-level rise. In the Everglades, it is believed that mangroves will simply colonize wetlands further inshore as sea level rises (Davis *et al.,* 2005). This may not be possible along the SEFC, as much of the more upland habitat inshore of the mangrove forests has been lost to urbanization (discussed below).

The effect of global climate change on the frequency of hurricanes in the North Atlantic is not well understood, but increased sea surface temperatures have been demonstrated to increase the number and intensity of hurricanes since the 1970s (IPCC, 2007). The IPCC (2007) predicted a global decrease in cyclone formation and an increase in their number and intensity in the North Atlantic, based on their prediction of higher sea surface temperatures in that basin. This increase would result in greater frequency and intensity of strikes along the SEFC. As was demonstrated from Hurricane Andrew in 1992, intense storms can destroy entire mangrove forests (Pimm *et al.,* 1994). The interaction of hurricanes with sea-level rise can have synergistic impacts.

Although the greatest threat posed by global climate change is the steady increase in mean temperature, most models indicate that there will be greater variance in temperature as well (IPCC, 2007). This suggests that, although the mean temperature along the SEFC will likely increase, there will also be greater variability around that mean including, possibly, more frequent and severe cold events. In January of 2010 and 2011, significantly low temperatures occurred that resulted in large fish kills in the marine environment of the SEFC (personal observation). Although there was little damage to mangrove trees, the events in consecutive years may be a harbinger of more frequent and severe cold stresses.

Altered Shoreline and Circulation Patterns

Barbier *et al.* (2011) reviewed the loss of estuarine and coastal ecosystems worldwide due to anthropogenic stressors. They indicate that 35 percent of the world's mangrove habitat has been destroyed. Both mangrove and upland habitats have been extensively destroyed along the SEFC on islands that are connected by roadways, largely due to urbanization (Strong and Bancroft, 1994).

The impoundment of mangrove forests can result in sudden mangrove mortality if water levels behind the impoundment result in flooding of the upper root zone, thereby drowning the trees (Odum *et al.,* 1982). If the effect of the impoundment is to make the mangrove forest dryer, the mangrove will gradually be replaced by more upland species through successional changes (Odum *et al.,* 1982).

A possible means for altering circulation patterns that could alter mangrove habitats are proposals to remove some of the dredge and fill causeways created by the Flagler East Coast Railroad and the U.S. 1 Highway road bed (e.g., the Florida Keys Feasibility Study and Florida Keys Tidal Channel Demonstration Project, which are both part of the Comprehensive Everglades Restoration Plan; U.S. Army Corps of Engineers, 1999). These projects are designed to restore more natural circulation patterns between the Florida Keys, thereby presumably undoing damage caused to both the coral reef and Florida Bay due to the lack of circulation (U.S. Army Corps of Engineers, 1999). Although necessary to accomplish true habitat restoration, these projects will likely result in the loss of mangrove spatial extent (U.S. Army Corps of Engineers, 1999).

Invasive Species

Globalization of markets has resulted in unprecedented alterations in the distribution of the earth's biota (Mack *et al.,* 2000). Mack *et al.* (2000) indicate that animal invaders can alter their adopted habitats through predation and competition with native species, as well as through grazing and habitat alteration. Plant invaders change their adopted habitat through changes in fire regime, nutrient cycling, hydrology, and energy budgets, thereby changing the habitat at its most basic level (Mack *et al.,* 2000). Numerous exotic species have successfully invaded South Florida and the Florida Keys (Engeman *et al.,* 2011; Gordon, 1998; Trexler *et al.,* 2005), possibly due to the tropical environment and relatively low diversity of flora and fauna generally associated with tropical and subtropical environments (Mack *et al.,* 2000).

Mechanisms of Change: Description of Ecological Processes

Mangrove Die-Off

Mangroves are well adapted to thrive in anaerobic soils (Walsh, 1974). These adaptations include a shallow root system and root specialization that allow the portion of the root just above the water surface to take in oxygen and distribute it to the roots in the anaerobic environment (Walsh, 1974). If these root specializations become coated or clogged, oxygen is blocked from the roots and the plant dies (Odum *et al.,* 1982). Studies performed after two oil spills near the Panama Canal documented the immediate loss of mangroves that were coated by the spill (Jackson *et al.,* 1989; Duke *et al.,* 1997) and that the damage was persistent for years after the spills (Duke *et al.,* 1997). The presence of oil tankers offshore near the SEFC and drilling activities along the coast of Cuba could result in an oil spill that reaches and destroys these mangroves.

Sea-level rise can also result in mangrove die-off. If the specialized root systems become flooded, the roots can not respire and the tree will drown (Walsh, 1974). The end result would be spatial loss of mangroves if the higher estimates take place. This would be the direct impact of sea-level rise if mangrove sediment production can not keep pace with sea-level rise (Twilley *et al.,* 2001). Even if sedimentation rates can keep pace with the rising sea, tropical storms can remove both trees and sediments from wetlands, leaving behind a habitat unsuitable for mangrove colonization (Wanless *et al.,* 1994).

Mangroves are susceptible to cold stress that takes the form of defoliation and death (Stevens *et al.,* 2006). Olmstead *et al.* (1993) documented the extensive damage to mangroves in Everglades National Park due to freezes in 1977, 1981, and 1989. The December 1989 freeze was particularly virulent. Overnight temperatures dropped to approximately freezing for two consecutive nights along the lower east coast of Florida (NOAA, 1989). This resulted in the defoliation of hundreds of square kilometers of dwarf red mangrove forest along the extreme southeastern coast (personal observation). If global climate change does result in lower extreme temperatures along the SEFC, such impacts may become more common and more severe.

Conversion of Habitat

Strong and Bancroft (1994) documented the destruction of 44 percent, 50 percent, 65 percent, and 39 percent of mangrove forests on southern Key Largo, Plantation Key, and Upper and Lower Matecumbe Keys, respectively, principally due to conversion to dredge and fill subdivisions prior to 1991. Strong and Bancroft (1994) estimated the loss of upland hammock forest at 64 percent, 70 percent, 76 percent, and 69 percent for southern Key Largo, Plantation Key, and Upper and Lower Matecumbe Keys, respectively. Although current and future losses of both mangrove and upland habitat along the SEFC are well regulated, losses still continue through permitted and illegal clearing of the habitats in urbanized areas (personal observation). Legislation can also be changed to relax restrictions on development in wetlands, in general, and mangroves specifically. Loss of upland habitat along the SEFC can also affect mangroves in combination with sea-level rise. In places like Everglades National Park, mangroves are expected to remain the same or increase in size, with an expansion inland and concomitant loss shoreward (Pearlstine *et al.,* 2009). Along the SEFC, much of the inland habitats have also been destroyed through urbanization, thereby removing inland sea-level rise refuges.

Odum *et al.* (1982) documented that impoundments created on SEFC wetlands resulted in the death of trees. Impoundments can kill the enclosed forest due to both over flooding and over drying of the habitat (Odum *et al.,* 1982). Impoundments can also change the type of forest (e.g., from overwash to basin forest: Rey *et al.,* 1990) and, in the process, change the species composition of the forest. Nutrient limitation within impoundments can stunt tree growth, resulting in a dwarf mangrove forest type. Impoundments can also stunt the growth of trees through nutrient limitations (Feller *et al.,* 2003). Persistent hypersaline conditions within impoundments have also been shown to kill the impounded forest (Rey *et al.,* 1990).

There are plans within the Comprehensive Everglades Restoration Program to remove many of the causeways created by the Flagler Railroad and U.S. 1 Highway (USACE, 1999). These causeways increased the spatial habitat of mangroves by reducing flow rates and allowing the establishment of propagules on many mud flats adjacent to the roadway. Restoring the flow may result in the direct destruction of these forests or their inability to re-establish after a catastrophic event (e.g., hurricanes, freezes).

Coastal Land Loss

Wanless *et al.* (1994) demonstrated that intense storms in 1935 and 1960 removed not only mangrove forests but also washed away much of the soil. Until the storms struck, mangroves were able to accrete soils to keep pace with sea-level rise. When these soils were washed away, along with the trees, the resulting habitat was too deep for mangrove propagules to establish themselves, leaving open mud flats where dense forest once stood (Wanless *et al.,* 1994). In this way, both hurricanes and the combination of hurricanes and sea-level rise can result in the permanent loss of mangrove habitats.

Ecological Processes that Affect Fish and Birds

A decrease in the spatial extent of mangrove forests along the SEFC will eliminate highly productive habitats for the small demersal resident fishes that make up the prey base for both predatory fish and piscivorous birds (e.g., Lorenz, 1999; Lorenz and Serafy, 2006). Changes in forest type or tree species composition will alter the type of fish community that utilizes these habitats. Forest declines will also eliminate critical nesting habitat for myriad bird species (Odum *et al.,* 1982) and eliminate important foraging grounds for these species (Lorenz *et al.,* 2002). Studies of fishes in the mangrove forests of southern Florida show that fish species composition is highly variable, depending on the forest type and the tree species composition of those forests (western Florida Bay: Thayer *et al.,* 1987; northeastern Florida Bay: Ley *et al.,* 1999; Lorenz, 1999; Lorenz and Serafy, 2006; Biscayne Bay: Serafy *et al.,* 2003; and the southeastern Everglades: Faunce *et al.,* 2004). The increased structural complexity of mangrove root systems has been demonstrated to decrease predator efficiency (Primavera, 1997); forest type and tree species composition thus determine the use of habitats as nursery grounds for juvenile game fish species, as well as the forest use for piscivorous fish and birds. Changes in mangrove forest type and species composition also determine the suitability of nesting habitat for many bird species. For example, white-crown pigeons require dense canopy, while several species of wading birds nest in more open canopy (Powell, 1987; Strong *et al.,* 1994). Changes in forest structure and type may change the suitability of the forest as a nesting habitat for specific bird species.

Invasive Species Competition and Predation

At least two species of Indo-Pacific mangroves have been established in southern Florida and are expanding their ranges and displacing native mangroves (Fourqurean *et al.,* 2010). Invasive upland species, such as Brazilian pepper (*Schinus terebinthifolius*; Lass and Prather, 2004) and Australian pines (*Casuarina equisetifolia*; personal observation), have also displaced mangroves in areas of low salinity and higher elevations. Introduced animals can also have a direct impact on mangrove forests. For example, mangroves have been found susceptible to damage from native foliovores (Saur *et al.,* 1999) and wood boring organisms (Rehm and Humm, 1973). It is conceivable that the introduction of more noxious species of such organisms may result in extensive damage to mangrove forests. Introduced vertebrates can also cause extensive damage as demonstrated by the nearly complete destruction of the mangrove forest of Lois Key in the lower Florida Keys by a food-subsidized colony of free roaming rhesus monkeys (personal observation, also see http://www.cnn.com/TECH/science/9807/10/monkey.island/). Introduced animals can also have a direct impact on the community structure within mangrove forests by out competing or preying upon native species (e.g., Barbour *et al.,* 2010; Trexler *et al.,* 2000).

Marine Debris

The root adaptations of mangroves capture and hold human-related refuse items (e.g., bottles, cans, marine industry jetsam). Although these items rarely damage the trees, fauna can become trapped or tangled in this refuse. Personal observations of SEFC mangroves include birds and manatees that had become ensnared in monofilament fishing line; fish, diving birds, and reptiles (including an endangered American crocodile) that had become tangled in discarded nets; and fish and invertebrates that had become trapped in discarded bottles.

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Marine-Dependent People

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In a nutshell

- Marine-dependent people are people engaged in activities directly related to the coastal marine environment, for commerce or recreation, or indirectly by providing services that support these activities.
- Marine-dependent people play an important role by providing the demand for or facilitating the delivery of ecosystem services.
- Changes in the coastal marine environment affect marine-dependent people by altering the level of benefits able to be delivered as ecosystem services.
- Regulations to protect or restore the coastal marine environment affect the ability of marine-dependent people to access benefits provided by ecosystem services.

Define Resource

In a departure from the approach taken in the other MARES subregions, participants in the conceptual model workshop for the SEFC elected to incorporate people explicitly as a component in the *State* element of the DPSER model framework. The "marine-dependent people" submodel includes the people in the region who engage in activities directly related to the coastal marine environment, for commercial fishing and recreation, as well as the people who are indirectly engaged because they provide support for these activities. Marine-dependent people can be classified as primary users, secondary users, or tertiary users based on the degree to which their activities take place in or near the coastal marine environment (Table 1).

Primary users are those individuals or groups who actively engage in activities in or on the water and who are directly dependent on the marine resource. The economic study of the recreational use of the Florida reef by Johns *et al.* (2001) identified primary users as "boaters who are recreational fishers, reef divers, reef snorkelers, and/or visitors viewing the reefs on glass-bottom boats." As defined here, primary users include similar users of other coastal marine habitats, i.e., hardbottom communities, seagrass beds, coastal wetlands, mangroves, and beaches, and commercial fishers in addition to the strictly recreational users identified by Johns *et al.* (2001).

Secondary users are one step removed from direct interaction with the marine resource, but who provide enabling support for the primary users.

Tertiary users are those who don't directly interact with the coastal marine environment, but whose activities support the primary and secondary uses.

Table 1. Activities engaged in by marine-dependent people.

Primary Users	Secondary Users	Tertiary Users
1. SCUBA divers/snorkelers	8. Marinas	13. Hotels
2. Recreational fishermen	9. Bait and tackle shops	14. Restaurants and fish houses
3. Swimmers, surfers, other non-motorized users	10. Boat rentals/other, commercial recreational providers	15. Souvenir shops
4. Commercial fishermen	11. Dive shops	16. Transportation services (e.g., bus, rental car, etc.)
5. Dive boat operators	12. Employees of secondary users	17. Service stores (seafood markets, grocery stores, departments, etc.)
6. Party/charter boat operators		18. Employees of tertiary users
7. Fishing guides		

Similar categories are used by others to identify people who depend directly on the coastal marine environment either for their livelihood or for recreation (cf., Johns *et al.,* 2001, 2004). The group identified as stakeholders in the Florida Department of Environmental Protection's Coral Reef Conservation Program is more inclusive, including management agencies at the federal, state, and local level, researchers, non-governmental organizations, port authorities, environmental consultants, teachers, and water resource managers in addition to the primary users defined here (Jamie Monty, personal communication). In comparison to the marine economy as described by Pendleton (n.d.), "marine-dependent people" identified here correspond to the commercial fishery sector and coastal and estuarine recreation sector, combined. The entire marine economy defined by Pendleton includes these additional sectors—critical energy infrastructure, marine transportation, and coastal real estate—as comprising the marine economy.

Geographic extent

Marine-dependent people make use of the entire SEFC marine ecosystem.

Role of Marine-Dependent People in the Ecosystem

Marine-dependent people play an intermediary role in the delivery of *Ecosystem Services* provided by the coastal marine ecosystem (Figure 1; Table 2). The class of primary users includes most of the recreational users in the coastal marine ecosystem. Primary users also include commercial fishers, who harvest the seafood that constitute the provisioning service to the general human population. The activities of primary users directly impact other components of the coastal marine environment through various Pressures. For example, the harvest activities of both recreational and commercial fishers have a significant effect on the species composition and population characteristics of fish and shellfish.

The activities of secondary and tertiary users of the coastal marine environment support the activities of primary users. This support facilitates the provision of Ecosystem Services. Often, this is essential, as in the role of marinas and dive shops, in providing access for primary users into the coastal marine environment, but the activities of secondary and tertiary users generally occur on land as opposed to in or on marine waters.

The activities of primary, secondary, and tertiary users are affected by changes in other components of the coastal marine environment. This connection occurs through the set of "attributes people care about" that characterize the condition of other components of the environment (Table 3).

Key Attributes of Marine-Dependent People

Two types of information can be used to quantitatively characterize marine-dependent people. The first consists of various measures of the intensity of their individual

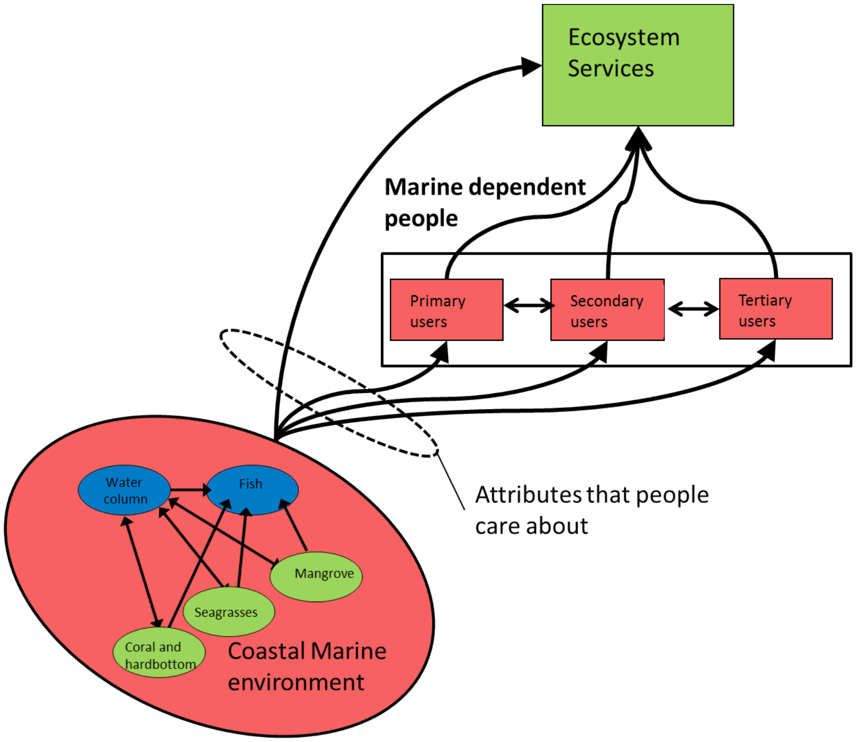

Figure 1. All marine-dependent people receive *Ecosystem Services* directly or indirectly and some act as intermediaries between these services and non-marine dependent people (e.g., commercial fishers providing fish for non-fishers).

activities. Information routinely collected on commercial fishing is an example of the first type of information. Information is collected on the types and amount of fish harvested and "landed" in port. Additional information can be collected to estimate the effort expended by commercial fishers in acquiring their catch, and this leads to the calculation of catch per unit effort, which is often taken as a measure of the abundance of the fished stock. The second type of information consists of measures of the number of people participating in these activities. Information on the number of participants can be collected directly, via surveys of actual use, and indirectly via the results of licensing activities. For example, the number of boat licenses issued annually provides information on the magnitude and trends in recreational versus commercial activities among primary users (Figure 2).

Information collected on marine-dependent people can be analyzed to estimate the magnitude, or value, of their activities in economic terms. This allows for comparisons to be made about the scale of the activities of marine-dependent people versus other sectors of the marine economy (cf., Pendleton, nd.) and other sectors of the general regional economy. The studies by Johns *et al.* (2001, 2004) employed extensive survey research to measure the economic contribution and the use values of artificial and natural reefs over the 12-month period of June 2000 to May 2001. The reef users surveyed were boaters who are recreational fishers (commercial fishers were not included), reef divers, reef snorkelers, and/or visitors viewing the reefs on glass-bottom boats. Economic contribution was measured by total sales, income, employment, and tax revenues generated within each county. In addition, the opinions of resident reef-using

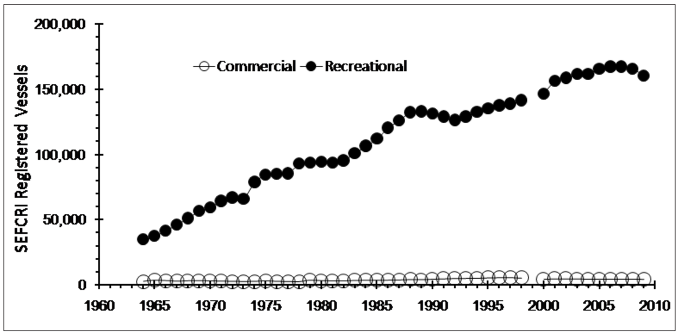

Figure 2. Licensed commercial and recreational vessels (data compiled by J. Ault).

Table 2. Ecosystem services in which primary, secondary, and tertiary users serve as intermediaries in their delivery (numbers refer to users identified in Table 1).

Ecosystem Service	Primary Users	Secondary Users	Tertiary Users
1. Beautiful, unique environment			15
2. Opportunity for beach activities and shoreline views	7	10	13, 14, 16
3. Opportunity for wildlife recreation activities		10	16
4. Protection of wildlife species			
5. Opportunity for bird-watching activities		10	16
6. Opportunity for recreational fishing, diving, snorkeling, and boating	5, 6, 7	8, 9, 10, 11	16
7. Clean air and quality of life			
8. Resources for research and development (e.g., inventions, new cures for illness)			
9. Living laboratory for education (K-12, colleges, and universities)			
10. Protection of wildlife species and habitats for current and future generations			
11. Protection of property from storm damages			
12. Supply of a variety of high-quality seafood	4		
13. Storm water retention, water treatment, nutrient cycling, and compliance with regulations			
14. Stable climate			
15. Opportunity to harvest commercial fish species	6, 7	8	
16. Opportunity to catch recreational fish species	6, 7	8, 9, 10	
17. Opportunity for subsistence fishing		8, 9	

boat owners regarding the existence or establishment of "no-take" zones as a tool to protect existing artificial and natural reefs were presented.

Drivers of Change in Primary Use

Changes in primary use occur in response to environmental changes, regulations, and economic and/or social factors that affect demand for *Ecosystem Services* provided by the coastal marine environment. As a *State* component in the DPSER framework, marine-dependent people are sensitive to the effects that *Drivers* and *Pressures* exert on other components of coastal marine environment of the SEFC. The *Response* by management agencies can affect access to the coastal marine environment by marine-dependent people, sometimes by providing facilities and enforcing regulations that increase access and sometimes by enforcing regulations that restrict access. Frequently, as in the case of the sanctuary preservation areas implemented by the Florida Keys National Marine Sanctuary, the main effect of regulation is to manage conflicts between competing uses of the coastal marine environment.

In addition to these environmental factors, the uses of the coastal marine environment by marine-dependent people are also affected by economic and other social factors that influence the demand for *Ecosystem Services*. This is a

Table 3. Attributes people care about specific to primary, secondary, and tertiary users (numbers refer to users identified in Table 1).

Attributes People Care About	Primary Users	Secondary Users	Tertiary Users
Aesthetics—on land	3		13, 14
Aesthetics—water-based recreation	1, 2, 3	8, 9, 10, 11	
Lots of healthy coral	1, 3, 5		
Lots of and large variety of fish	1, 2, 3, 4, 5, 6, 7		14, 17
Lots of and large variety of large wildlife (manatees, dolphins, sea turtles, game fish, sharks)	1, 2, 3, 5, 6, 7		
Quality of beaches and shoreline	3		13, 14
Ecosystem resilience to disturbance	1, 2, 3, 4, 5, 6, 7		
Coastal erosion and storm protection—buildings and boats	4, 5, 6, 7		
Air quality and odor			13, 14
Environmental education and research	4, 5, 6, 7		
Seafood safety			14, 17
Large variety and numbers of birds	3		
Critical habitat for protected species (e.g., tree snails, smalltooth sawfish, sea turtle, Cape Sable seaside sparrow, orchids, goliath grouper)	1, 3, 5, 6, 7		
Natural filter for wastewater and storm water runoff			
Carbon sequestration			
Nutrient regulation—Converts nutrients to benign forms			

huge, complex, uncharted territory. Demand might be best characterized as a *Driver* that must be measured. We might be able to understand what causes a change in demand after the fact, but it is unlikely that we will be able to describe causal mechanisms for changes in demand that are predictive in any way.

Mechanisms Leading to Changes in Primary Use

Changes in the use of *Ecosystem Services* by primary users that are not related to changes in demand can be described in terms of changes in satisfaction by the user. Satisfaction is typically viewed as one of the most important management goals when providing quality recreational opportunities. Unfortunately, satisfaction is a difficult concept to measure. Simply asking an individual how satisfied they are does not inform a manager why they are or aren't satisfied, or what contributed to their response. Other factors must be considered that include subjective personal and social aspects of a user's experience; these include conflict, crowding, expectations, normative standards, etc. While these other factors can be easily justified on their own (particularly for the commercial operators), they need to be considered when seeking to understand satisfaction.

The recreational user seeks satisfaction in the experience of obtaining a desired *Ecosystem Service* facilitated/delivered through resource management. The satisfaction sought by a recreational user has two parts: the environmental and the social. The first, the environmental, is determined by the attributes typically thought of as being provided via a marine ecosystem; these are characterized by the "attributes people care about." The second, the social, is determined by interactions with other people. These are related to conditions that individuals often think of as services when participating in their activity. It should be noted that there are additional social "services" that should be considered for inclusion. These might include relaxation, solitude, education, family time, etc. These services are not based directly on physical attributes, but rather management goals in combination with the resource.

Crowding

Perceived crowding is a concept that is at best only weakly related to user density. Instead, it is related to factors such as goal interference, expectations and discrepancies, normative standards, etc. The "*Ecosystem Service*" being desired by users, and delivered through resource management, would be a mix of user types, use levels, and experiences consistent with what the combination of the resource and management goals are intended to provide.

Conflict

Conflict is typically defined by the mixing of motorized and non-motorized users. The two typically don't prefer to mix. A second characteristic of conflict is that it is typically asymmetrical in that one group (fishermen, for example) will experience conflict while the other group (motor boaters or skiers, for example) will not experience conflict. Conflict is related to perceived crowding, which is then related to satisfaction.

Expectation

Humans do things in the expectation that certain outcomes (*Ecosystem Services*) will follow. Users in this case have certain expectations for certain *Ecosystem Services*. They might expect certain numbers of fish to catch, or numbers (not too many or too few) of other divers to be in the water at the same time, or a healthy and pristine ecosystem. This does not mean that user expectations should automatically be met. Expectations are often unrealistic or inappropriate for a given environmental condition or management mandate. Instead, expectations should be considered in the sense that they influence how users evaluate conflict, crowding, or satisfaction. Thus, expectations aren't a true *Ecosystem Service* but rather an intervening variable in understanding other ecosystem services.

Normative Standards

Normative standards are socially agreed upon standards of what should be. Users can generally agree on what constitutes an acceptable level of coral bleaching, or use levels, or coastal impacts due to human use, or management mandates for particular resource types or classifications. It is usually necessary and best to examine norms according to meaningful subgroups, since an overall average user really doesn't exist. Like expectations, norms are not *Ecosystem Services*. They are the standards against the extent to which *Ecosystem Services* are being delivered or met. They are a comparative device.

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