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Integrated Conceptual Ecosystem Model Development for the Florida Keys/ Dry Tortugas Coastal Marine Ecosystem

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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 sub-regions 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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Table of Contents

Preface i

Figures and Tables v

Acronyms vi

Abstract...vii

Introduction...1
- Three Distinct Subregions within the South Florida Coastal Marine Ecosystem...........................1
- Oceanographic Processes Connect Subregions 2
- Building a Foundation for Ecosystem-Based Management...4
- The MARES Model Framework...5

The Florida Keys/Dry Tortugas 7
- Physical Setting..7
- Connectivity 8
- Human Population 8

The Florida Keys/Dry Tortugas Integrated Conceptual Ecosystem Model......................................9
- Conceptual Diagram: Picturing the Ecosystem 9
- Applying the Model in the FK/DT: Sewering the Keys 9

Drivers and Pressures: Sources of Change...12
- Far-Field Drivers and Pressures 12
- Near-Field Drivers and Pressures...14

State: Key Attributes of the Ecosystem...16
- Water Column..16
- Fish and Shellfish...16
- Benthic Habitats...17
  - Coral and Hardbottom 17
  - Seagrasses 17
  - Mangroves...18

Ecosystem Services: What People Care About 18
- Attributes People Care About: Linking State to Ecosystem Services 18
- Valuing Ecosystem Services..20

Table of Contents (continued)

Response: Taking Action 20
Controls on Development 21
Protected Areas 21
Florida Keys National Marine Sanctuary and Protection Act 21
Dry Tortugas National Park 23
State Parks and Federal Refuges 23
Ecosystem Research and Monitoring 23
Southeast Florida Regional Climate Change Compact 23

References 24

Appendices
Water Column 29
Fish and Shellfish 41
Benthic Habitat: Coral and Hardbottom 52
Benthic Habitat: Seagrasses 67
Benthic Habitat: Mangroves 81

Figures

1. Map of the South Florida coastal marine ecosystem and three MARES subregions....................1
2. Oceanographic processes in the South Florida coastal marine ecosystem 2
3. The MARES Drivers-Pressures-State-Ecosystem Services-Response (DPSER) model................6
4. Map of South Florida depicting the Florida Keys/Dry Tortugas 8
5. Population centers in the Florida Keys 9
6. The Florida Keys/Dry Tortugas and the factors affecting their condition 10
7. The Florida Keys/Dry Tortugas State model 11
8. Human population in the Florida Keys 21
9. Map of the Florida Keys National Marine Sanctuary...22
10. Unified southeast Florida sea-level rise projection for regional planning 24

Tables

1. Far-field drivers and pressures of greatest importance to the Florida Keys/Dry Tortugas 13
2. Near-field drivers and pressures of greatest importance to the Florida Keys/Dry Tortugas.......15
3. Ecosystem services provided by the South Florida coastal marine ecosystem..........................19

Acronyms

CERP	Comprehensive Everglades Restoration Plan
DPSER	Drivers-Pressures-State-Ecosystem Services-Response
EBM	Ecosystem-based Management
EI	Ecosystem Index
FKNMS	Florida Keys National Marine Sanctuary
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 MARine and Estuarine goal Setting (MARES) 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 by both policy makers and by natural resource and environmental management agencies. The document that follows briefly describes the MARES project and this systematic process. It then describes in considerable detail the resulting output from the first two steps in the process, the development of conceptual diagrams and an Integrated Conceptual Ecosystem Model (ICEM) for the first subregion to be addressed by MARES, the Florida Keys/Dry Tortugas (FK/DT). What follows with regard to the FK/DT is the input received from more than 60 scientists, agency resource managers, and representatives of environmental organizations beginning with a workshop held December 9-10, 2009 at Florida International University in Miami, 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 first report of the MARES project, documents the development of a conceptual ecosystem model for the coastal marine waters surrounding the Florida Keys/Dry Tortugas (FK/DT). 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 will 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

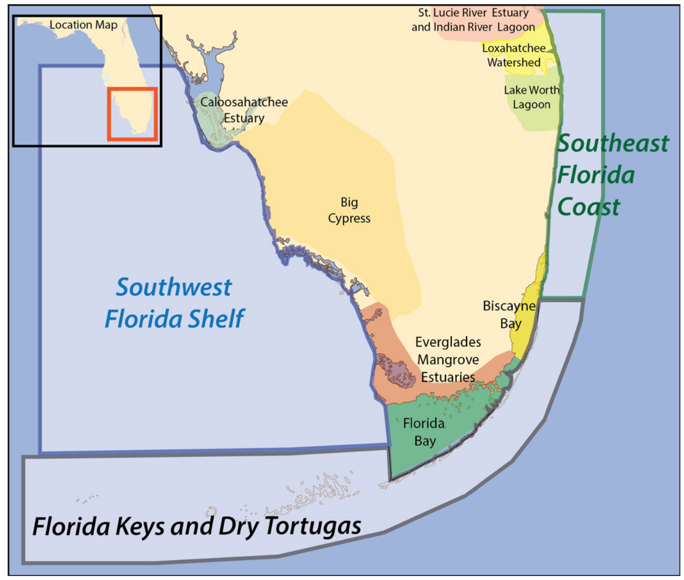

Figure 1. Map of the South Florida coastal marine ecosystem and three MARES subregions.

the Southwest Florida Shelf (SWFS), the Florida Keys/Dry Tortugas (FK/DT), and the Southeast Florida Coast (SEFC). The SFCME also includes two large estuarine embayments—Florida Bay and Biscayne Bay—and several smaller estuarine systems, such as the Caloosahatchee Estuary.

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 regions 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 ecosystems (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 seven 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 *Ecosy*stem 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 FK/DT 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 as a link between *Ecosystem Services* and the *State* of the

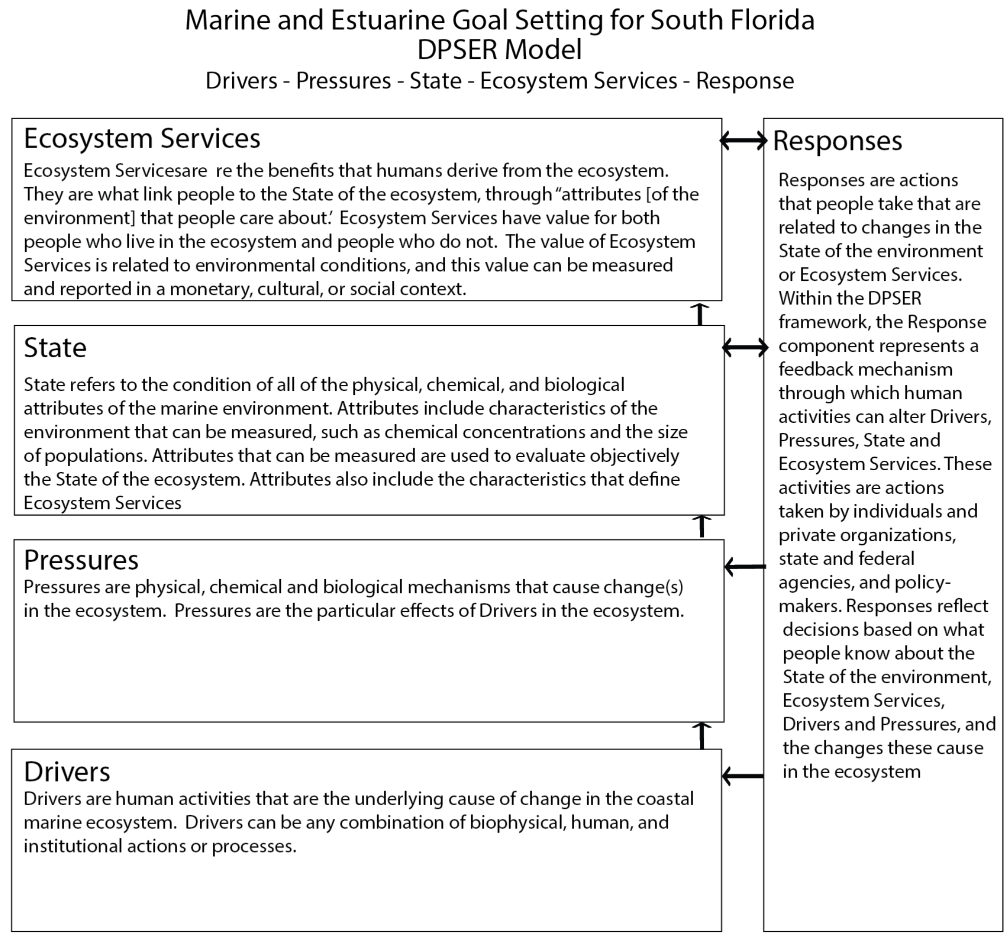

Figure 3. The MARES Drivers-Pressures-State-Ecosystem Services-Response (DPSER) model.

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 FK/DT 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 Florida Keys/Dry Tortugas

Physical Setting

The FK/DT comprises a chain of developed islands stretching from Key Largo to Key West that are connected by 110 miles of U.S. Highway 1, and continuing westward to the Dry Tortugas National Park, a chain of undeveloped islands (Figure 4). The Florida Keys is one of the most ecologically diverse and most imperiled ecosystems in the U.S. It contains a large part of North America's barrier coral reef ecosystem, which is the third largest barrier reef system in the world. The surrounding marine waters include the Florida Keys National Marine Sanctuary (FKNMS), the second largest marine sanctuary in the U.S. (Monroe County, 2011).

The FK/DT coastal marine ecosystem is composed of tropical to subtropical waters that contain diverse community types, including bank reefs, patch reefs, hardbottom, seagrass beds, and mangrove forests. The diversity of community types results in high species richness. The Florida Keys are a popular tourist destination, in part because the faunal richness and water clarity provide interesting snorkeling and diving venues. Furthermore, the shallow-water environments surrounding the Florida Keys contain extensive nursery areas and fishing grounds for a variety of commercially and recreationally important marine species.

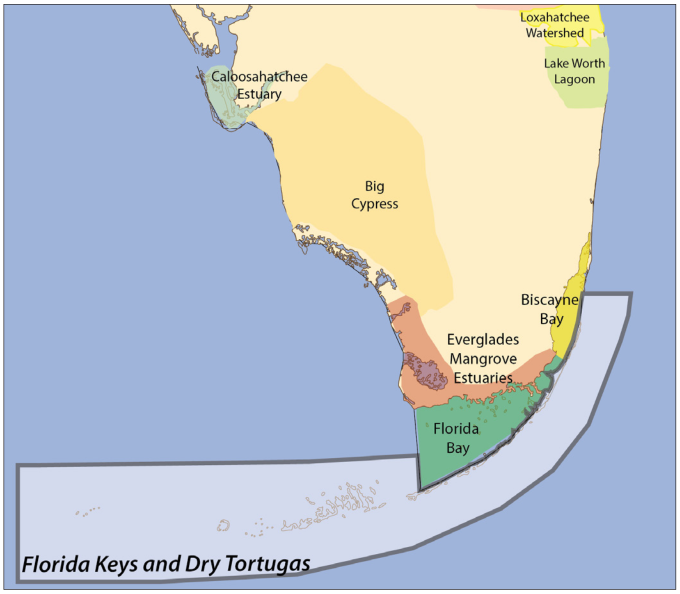

Figure 4. The Florida Keys are comprised of a chain of developed islands stretching from Key Largo to Key West that continue westward to the Dry Tortugas National Park, a chain of undeveloped islands.

Connectivity

The Florida Keys are integrally connected with respect to hydrology and ecosystem response to the Everglades watershed. Prevailing ocean currents link the FK/DT to the Everglades, Florida Bay, and the SWFS. Generally, water flows from the Gulf of Mexico via the Loop Current, passing through the FK/DT to the Atlantic Ocean, and is eventually entrained by the Florida Current and flows northeastward (Lee et al., 2002) (Figure 2). The FK/DT is strongly linked to upstream regions in the Gulf of Mexico, including the Mississippi River, by the major oceanic flows of the Loop Current and Florida Current (Ortner *et al.,* 1995). Thus, regional water management strategies and responses to stressors must include impacts associated with the entire eastern Gulf of Mexico.

Water quality and the condition of organisms in Florida Bay have been linked to Everglades' runoff from both Taylor Slough (in eastern Florida Bay) and Shark River Slough (on the SWFS) (Kelble *et al.,* 2007). Salinity changes were dramatic in the 20th century (Brewster-Wingard *et al.,* 1998). Tidal mixing and mean southward flows through the Florida Keys can result in a direct influence of Florida Bay and the SWFS on the habitats of the FKNMS (Lee and Smith, 2002).

Upwelling of deep waters from internal tidal bores, current meanders, and eddies provides a significant source of nutrients to the outer reefs of the Florida Keys reef tract. Because of the volume of the water involved, upwelling events may overwhelm other sources of nutrients to the reef tract (Leichter *et al.,* 2003; Sponaugle *et al.,* 2005; Hitchcock *et al.,* 2005). Storm events may also result in changes in circulation patterns that can result in nutrient enrichment (Zhang *et al.,* 2009).

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 occurred in the five southern counties adjacent to coral reefs (Palm Beach, Broward, Miami-Dade, Monroe, and Collier). In 2030, southeast Florida is projected to have a population of 8.5 million, 2.4 million more than in 2012 (South Florida Economic Forecasting Partnership, 2006). The population size of South Florida directly influences many regional- and local-scale drivers like coastal development, agriculture, wastewater, fishing, and boating.

In contrast with other areas of South Florida, the population of the Florida Keys (Monroe County) has been stable since the mid-1990s. The stabilized population is the result of a Rate of Growth Ordinance (ROGO) that was enacted in 1992, followed by a Non-residential Rate of Growth Ordinance in 2002. These ordinances were enacted in response to mounting concerns over impacts to the coastal marine environment. The ordinances have effectively limited the number of people living in the Keys through restrictions on the number of building permits issued annually. In 2010, Monroe County had 73,090 permanent residents, 6,499 fewer than it had in 2000 (Hobbs and Stoops, 2002; Bureau of Census, 2010). The population of the Florida Keys is evenly divided between five municipalities (Key West, Marathon, Key Colony Beach, Layton, Village of Islamorada), and unincorporated areas (Figure 5).

The number of seasonal residents and tourists in the Florida Keys exceeds the number of permanent residents, effectively doubling the population of the Keys and associated

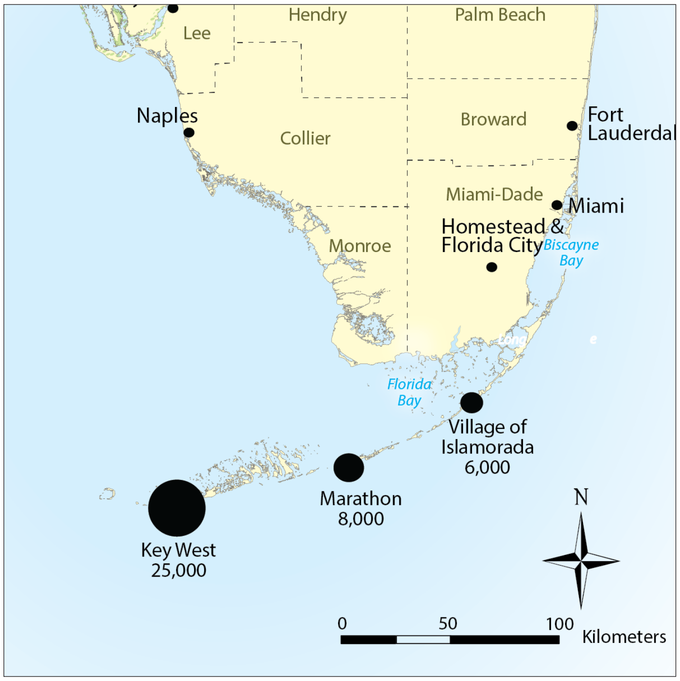

Figure 5. Population centers in the Florida Keys (Bureau of Census, 2010).

pressures on the coastal marine environment. On an average day during the winter season (December through May), there are an additional 43,600 to 44,500 visitors in the Florida Keys, making the functional population between 116,000 and 117,000 people. On a peak day, the functional population is estimated to be between 151,000 and 152,000 people (Leeworthy *et al.,* 2010). Recent growth in seasonal residents has offset the decrease in permanent residents since 2000. Therefore, the functional population of the Florida Keys has remained steady for the past decade (source: http://keyscompplan.com/facts-information-resources/comprehensive-plan-documents/).

The Florida Keys/Dry Tortugas Integrated Conceptual Ecosystem Model

Conceptual Diagram: Picturing the Ecosystem

As noted earlier, in the systematic MARES process, we first develop a conceptual diagram (here a cross-sectional infographic) of the ecosystem, the processes operating upon it, and the factors affecting its condition (Figure 6).

The FK/DT ecosystem consists of mangroves, seagrass, coral, and hardbottom habitats, as well as the overlying water column and the fish and shellfish that move among these habitats (see appendices for more information). Degradation of mangroves, seagrass, coral, and hardbottom habitats is a major concern in the FK/DT, because it reduces ecosystem services which Florida Keys residents rely upon, including recreational and commercial fishing and tourism. Local factors that affect the ecosystem and its services are wastewater, fishing, groundings, tourism, and land-use changes that alter sediment and toxin loading. Regional factors that affect the ecosystem include nutrient inputs to the water column, while global factors include rising water temperatures and ocean acidification. Not all aspects of this infographic apply to the Dry Tortugas given its geographic separation from the Florida Keys. This infographic is then expanded into a more complex and complete MARES DPSER model for this subregion (Figure 7).

Applying the Model in the FK/DT: Sewering the Keys

To illustrate how elements of the MARES DPSER model can be used to organize an analysis of an ecosystem management issue in the Florida Keys (Monroe County), consider the issue of wastewater discharge and a response that is currently underway. In this case, the human population in the Florida Keys is the main *Driver* threatening change in the ecosystem. Specifically, the presence of human populations leads to an increased quantity of wastewater that needs to be removed from the Keys. Most often, septic tanks or cesspits meet this need. However, both septic tanks and cesspits can lead to seepage of wastewater into the surrounding substrate, which in the Keys is porous limestone. Because of the porous limestone, this seepage results in wastewater discharge to the nearshore environments. The discharge includes nutrients and microbes that have detrimental impacts on the nearshore environment. Nutrients cause phytoplankton blooms that decrease water clarity and decay, causing hypoxia in sediments and stratified canals. Nutrients can also cause macroalgal overgrowth of seagrasses and corals, leading to less desirable habitats. The discharge of wastewater microbes can affect the natural functioning of the microbial loop, which cycles nutrients and carbon and is present in all aquatic ecosystems. Additionally, the microbes released could cause disease and illness in humans and marine organisms.

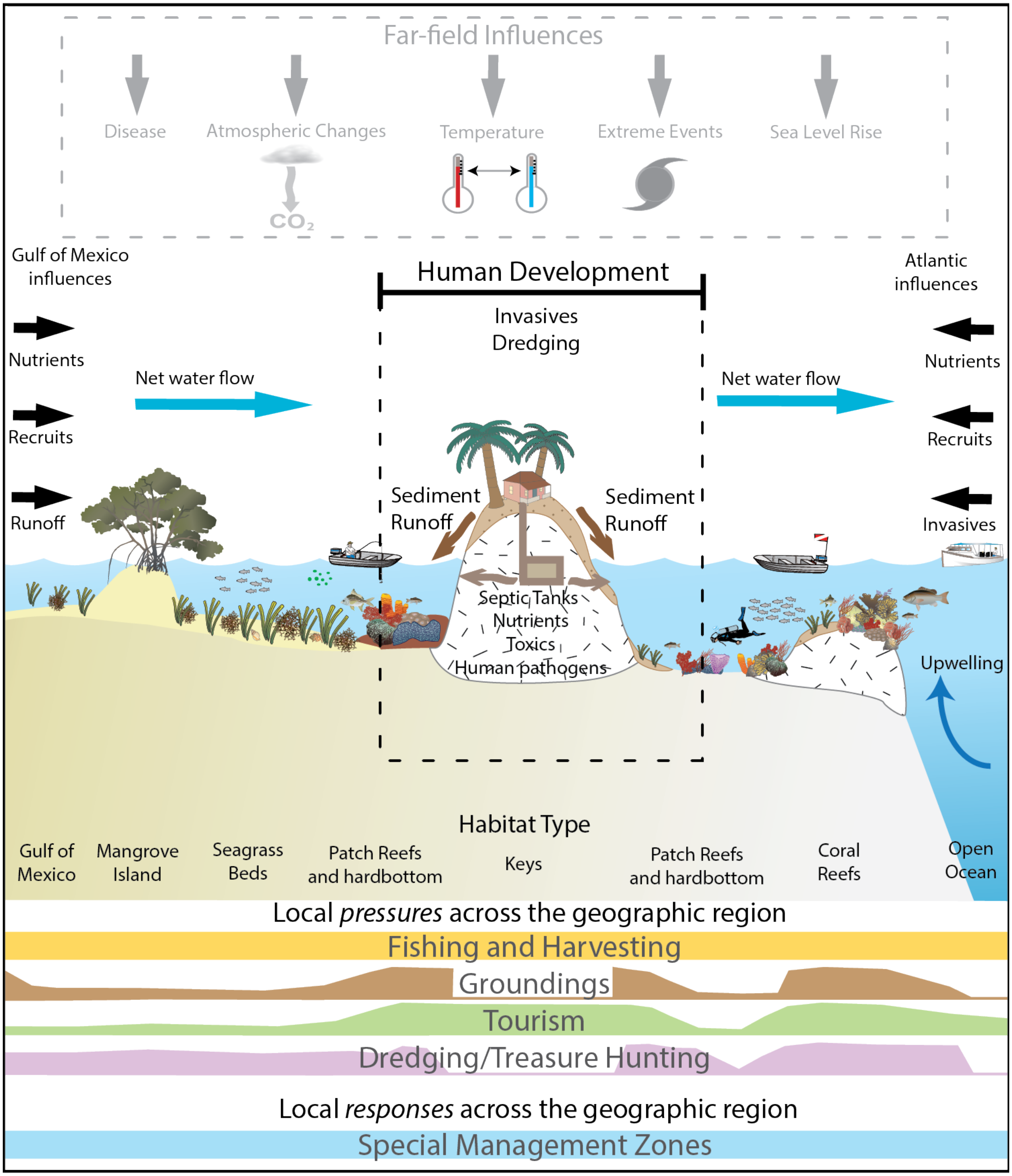

Figure 6. The Florida Keys/Dry Tortugas and the factors affecting their condition.

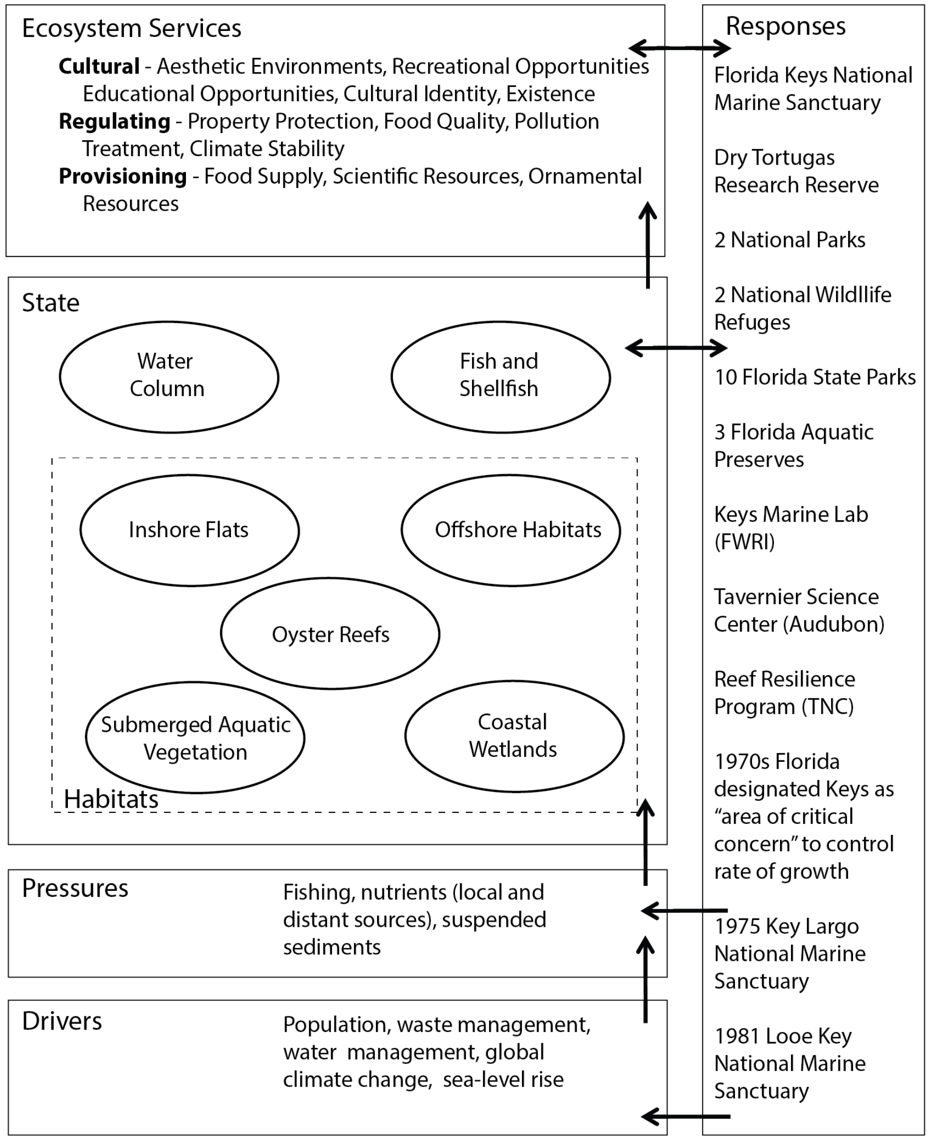

Figure 7. The Florida Keys/Dry Tortugas *State* model.

These impacts on the *State* of the nearshore environment decrease the quantity and quality of *Ecosystem Services* provided. The phytoplankton blooms decrease water clarity, impacting the quality of marine recreation, such as snorkeling. The hypoxia can enrich the sediments and bottom of the water column in stratified canals with sulfur, which results in an unpleasant odor when mixed by wind events, thus decreasing the aesthetics. The replacement of seagrass and coral with macroalgae significantly degrades the quality of marine recreation for divers and snorkelers, reduces habitat quality for fish and other wildlife, and affects pollution treatment by altering nutrient cycling rates. The release of the wastewater-associated microbes can cause health impacts in humans, making some areas of the marine ecosystem unusable. It can also cause health impacts in corals and alter the microbial loop and nutrient cycling.

Cesspits and failing septic tanks used for wastewater removal can impact the attributes of the nearshore coastal environment that people care about. These attributes are related to *Ecosystem Services* such as aesthetic quality and opportunity for recreational activities, e.g., beach activities, viewing wildlife, fishing, and seafood safety. The degradation of these attributes and loss, or threatened loss, of *Ecosystem*

Services motivated a *Response* by the Environmental Protection Agency, acting under the provisions of the Clean Water Act, to mandate that Monroe County reduce its reliance on cesspits and septic fields by providing municipal wastewater treatment.

Drivers and Pressures: Sources of Change

In this example, the human population is clearly a *Driver* and ocean acidification is clearly a *Pressure;* however, delineating the intervening steps (e.g., energy demand, fossil fuel burning, atmospheric CO_2) into *Drivers* or *Pressures* would be subjective at best. It is still important to capture the entire spectrum, as responses may act on any one of the processes within the spectrum. Delineating between far-field and near-field *Drivers* and *Pressures* is essential to determine the responsible management authority and to target those *Drivers* and *Pressures* that can be mitigated through the appropriate management body. In particular, it is useful to distinguish between *Pressures* arising from far-field causes and those arising from near-field causes within the FK/DT (Figure 6). 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 throughout the ecosystem. Far-field *Pressures* of concern in the Florida Keys include pressures related to climate change and pollution in freshwater runoff along the west coast of South Florida and from other, more distant sources. Near-field *Pressures* are generated internally, and their effect varies in intensity across the ecosystem. Near-field *Pressures* of concern include fishing, damage to benthic habitat from boating, invasive species (e.g., lionfish), and nutrients in runoff from the Florida Keys.

Far-Field Drivers and Pressures

Although far-field factors are outside of the realm of management control within the FK/DT, it is important that the general public and decision makers are aware of their influence to better understand the impact of management actions against the broader suite of *Pressures* acting upon the ecosystem (Table 1). Global processes that influence the Florida Keys 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 in the Florida Keys is climate change.

Long-term changes in ocean acidification, sea-level rise, sea surface temperature, rainfall, and hurricane severity and frequency are expected to occur as a result of natural and anthropogenic global climate variability. South Florida, with its low elevation, high coastal population density, and unique ecosystems, including the Everglades and coral reefs, will likely be dramatically affected by these changes. It remains to be seen just how, and to what extent, the salinity, water quality, and coastal circulation of South Florida's coastal waters, bays, and estuaries will be affected by global climate change.

Increasing concentrations of 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). Increased concentrations of CO_2 lower the pH of seawater, making it more acidic and decreasing the saturation state of aragonite. This makes it more difficult for marine organisms like corals to build and support their skeletal structures (Kleypas *et al.,* 2006; Manzello *et al.,* 2007). This potential impact on corals deserves significant attention in the Florida Keys because they are such an important contributor to the economy (Johns *et al.,* 2001). Increased concentrations of CO_2 and HCO_3^- (bicarbonate) also increase seagrass production (Hall-Spencer *et al.,* 2008), leaf photosynthetic rates (Zimmerman *et al.,* 1997), and plant reproductive output (Palacios and Zimmerman, 2007). Moreover, acidification will occur relatively slowly, allowing some organisms to adapt. Because the 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.

The FK/DT have a very low elevation and are one of the more vulnerable areas to sea-level rise in the U.S. The Intergovernmental Panel on Climate Change's (IPCC) 2007 projections for sea-level rise range from 20-60 cm during the 21st century; however, these rates do not include factors such as ice sheet flow dynamics that could significantly increase the rate. The more recent *Copenhagen Report* (Allison *et al.,* 2009) states that the IPCC (2007) report underestimated sea-level rise and that it may be as much as twice what has been projected. "For unmitigated emissions [sea-level rise] may well exceed 1 meter" by 2100, with an upper limit at approximately 2 meters (Allison *et al.,* 2009).

The global phenomenon of climate change and sea-level rise will alter the relative position of sea level, tides, and currents in the FK/DT. The geomorphology of the extensive shallow water areas surrounding the Keys, including numerous small mangrove islands found in these waters, reflect 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 occurred in coastal systems, including increased erosion and saltwater encroachment. Continuation of this rate will push marine water farther into freshwater environments, resulting in a substantial loss of freshwater wetlands (on mainland South Florida) and diminished groundwater resources. An important aspect of sea-level rise for the Florida Keys is that this will also push storm surge from tropical cyclones farther inshore.

Climate forecasts predict an increase in summer air temperatures of between 2-4ºC and an increase in winter air temperatures by 3ºC over the next century. Warmer temperatures will be accompanied by changes in rainfall and the frequency and intensity of storms (IPCC, 2007). Within the Gulf of Mexico, a 2-3°C temperature increase is predicted based upon IPCC scenarios and downscaled global climate circulation models (Liu *et al.,* 2000). These changes in temperature will have a significant impact on the biota of the Florida Keys, including corals, which are already living near their thermal maximum (Manzello *et al.,* 2007).

Table 1. Far-field drivers and pressures of greatest importance to the Florida Keys/Dry Tortugas.

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)

Near-Field Drivers and Pressures

Fisheries in the Florida Keys have been extensively exploited over the past 75 years. The snapper-grouper complex of 73 species of reef-dwelling fish is overfished relative to established benchmarks for sustainability of the stocks (Ault *et al.,* 2005). Fishing practices in the Keys are varied (Bannerot, 1990; Chiappone and Sluka, 1996). Recreational fisherman target adult reef fishes around bridges, piers, and on offshore patch and barrier reefs. Commercial and recreational fisheries also target Caribbean spiny lobster, marine aquarium fishes, and invertebrates, both inshore and offshore. Pink shrimp, a principal prey item of the snapper-grouper complex, are intensively exploited. Offshore, a substantial commercial food fishery targets adult pink shrimp inhabiting softbottom habitats near coral reefs. In coastal bays and near barrier islands, juvenile pink shrimp are commercially targeted as live bait for the recreational fishery. Both bait and commercial fisheries target pre-spawning subadult pink shrimp as they emigrate from coastal bay nursery grounds to offshore spawning grounds. Inshore, recreational fishermen pursue highly prized game fishes, including spotted seatrout, sheepshead, black and red drum, snook, tarpon, bonefish, and permit, while commercial fisheries primarily target sponges and crabs. Offshore of the deep margin of the barrier reef, fisheries capture an assortment of species including amberjack, king and Spanish mackerel, barracuda, sharks, and small bait fishes (e.g., *Exococtidae, Mullidae, Carangidae, Clupeidae,* and *Engraulidae*). Farther offshore (seaward of the 40 m isobaths), fisheries target dolphinfish, tunas, and swordfish, while recreational fishers target sailfish, wahoo, and white and blue marlin.

Recreational fishing trends are reflected by statewide fishing statistics and the number of registered boats. From 1964-2002, the number of registered recreational boats in South Florida grew by more than 500 percent. The increase in the number of fishing vessels has been accompanied by a number of technological advances that have been estimated to have quadrupled the average fishing power (Mace, 1997), i.e., the proportion of stock removed per unit of fishing effort (Gulland, 1983). These advances include improvements in fishing tackle, hydroacoustics (depth sounders and fish finders), navigation (charts and global positioning systems), communication, and inexpensive, efficient, and more reliable vessel and propulsion unit designs (Bohnsack and Ault, 1996; Ault *et al.,* 1997a, 1997b, 1998). These fishing trends have thus become an obvious concern to the sustainability of the fisheries and health of the coral reef ecosystem (Table 2).

Boating activities in the Florida Keys, for both commercial and recreational purposes, lead to unintended physical damage to coral, hardbottom, and seagrass habitats. This is the result of vessel groundings, propeller scars, and damage from anchors. Approximately 0.5 million lobster traps and one million stone crab traps are deployed in FKNMS waters during the fishing season. The impacts of lowering and raising such a considerable number of traps, as well as additional impacts from derelict fishing gear such as lost or abandoned crab and lobster traps ("ghost traps") and entangled lines, are not well known, but they could be considerable. Ghost traps capture indiscriminately and cause mortality of trapped species. Lost and discarded lobster, stone crab, and blue crab traps and related gear, such as ropes and buoys, are common components of marine debris in Florida.

Coral diseases are an increasing source of mortality to stony and soft corals in the Florida Keys and elsewhere (Bruckner, 2002). Moreover, coral diseases have been recognized as one of the key causal factors in the dramatic loss of coral cover recorded in the Caribbean over the past three decades (Aronson and Precht, 2001). The most common types of coral diseases—black-band, white-band, and white plague—have all been observed on Florida reefs (Bruckner, 2002). The prevalence of these diseases has been linked to human activities (Kruczynski and Fletcher, 2012).

The animal trade industry has resulted in the release of numerous non-native species to the South Florida coastal marine ecosystem. The prime example is the spread of lionfish, *Pterois volitans*, that now inhabit the Bahamas and east coast of the U.S., including the Florida Keys (Whitfield *et al.,* 2002, 2007). In the Bahamas, these predatory fish have been reported to kill an average of 1.44 native coral reef fish per hour (Cote and Maljkovic, 2010). This has resulted in a reduction of native fish recruitment by an average of 79 percent in reefs with *P. volitans* (Albins and Hixon, 2008).

Impacts from human development in the Florida Keys date from around 1912, the year in which Henry Flagler, the wealthy industrialist who developed much of the Florida east coast, completed a railroad between Miami and Key

West. The railway ceased operation due to damage from a 1935 hurricane, but a roadway built on the old track bed reestablished land transportation through the Keys in the early 1940s. This opened the entire island chain to development pressures and the human population spread to all of the islands along the rail route, growing exponentially until about 1990. A booming growth in tourism drove rapid development through the 1970s and 1980s. Beginning in the 1990s, the State of Florida and Monroe County have taken actions to curtail development and population growth in the Keys.

Although human population has been relatively stable for the last 20 years or so, changes in the composition of the Florida Keys' human population promise further changes in *Pressures* on the ecosystem. It is extremely important to understand the evolution of a tourist-based economy to a more permanent resident-based economy, as people who formerly were tourists retire to the Keys as permanent residents. Permanent residents demand a different set of goods and services than do tourists, which leads to a different footprint of development. This sets in motion multiplier impacts, as the types of goods and services provided and, thus, the patterns of development, change over time. Experience elsewhere has resulted in a "paradise lost" where the ecosystem can no longer deliver the *Ecosystem Services* once provided to the tourist population.

The initial impact of coastal development on the surrounding marine waters resulted from alteration of the shoreline by excavation, dredging, and filling in of mangrove wetlands and nearshore waters. Perhaps the principal, immediate impact of the construction of the railway was to alter water movement through channels between the islands along the railway route, which were either filled completely or obstructed by viaducts constructed to carry the track bed (Swart *et al.*, 1996). Extensive development during the 1970s and 1980s fueled the loss of mangrove shoreline habitat and the construction of numerous canals, which became hotspots for water quality problems from nutrients and contaminants introduced through stormwater and failing cesspits from residential and commercial developments.

Table 2. Near-field drivers and pressures of greatest importance to the Florida Keys/Dry Tortugas.

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)

Human habitation imposes a set of continuing *Pressures* on the marine ecosystem. These include altered freshwater inflows, e.g., from stormwater and associated contaminants; nutrient loads related to sewage disposal, lawn maintenance, and agriculture; and incidental/accidental inputs of contaminants and trash. The two main problems associated with pollution from wastewater are fecal contamination and nutrient enrichment. Cesspits installed for the disposal of domestic sewage constructed during the development boom of the 1970s and 1980s are ineffective at reducing nutrient levels before the discharged wastewater reaches marine waters, and many of these systems are still in use. Stormwater runoff carries nutrients and other pollutants, such as oil and metals, which accumulate on roadways. Facilities for collecting and treating stormwater before it's discharged into marine waters are largely non-existent. Stormwater runoff accounts for about 21 percent of the nitrogen and 45 percent of the phosphorus discharged to marine waters in developed areas of the Florida Keys (Kruczynski and McManus, 2002).

Changes in the water quality of surrounding ocean waters (Atlantic and Gulf of Mexico) exert a major influence on the quality of coastal waters in the Florida Keys. Changes in sea surface temperature, nutrient concentrations, contaminants, pH, and the occurrence of harmful algal blooms are particularly important. Concentrations of nutrients and contaminants are affected by inputs from the Florida Keys, South Florida mainland, and other more distant sources.

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 an environment that represent its overall condition (Ogden *et al.,* 2005). The marine waters of the Florida Keys support an ecologically-diverse environment. The marine environment in the region is divided into five components to better describe their defining attributes and underlying processes: (1) water column; (2) fish and shellfish; and three habitat communities (3) coral and hardbottom; (4) seagrass beds; and (5) mangroves. *State* submodels for each are provided as appendices to this report.

Water Column

The water column submodel encompasses the physical, chemical, and biological characteristics of the water column, including benthic sediment, phytoplankton, and zooplankton suspended in the water column. Currently, the Florida Keys ecosystem is highly oligotrophic, i.e., low phytoplankton biomass, low nutrient concentrations, an abundance of oxygen, 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, hardbottom, and coral reefs. In turn, these benthic habitats support the highly valuable and productive fish community.

The Florida Keys' geophysical setting produces dynamic oceanographic conditions, including intricate recirculating gyres and some of the strongest surface currents in the world (Lee *et al.,* 2002). These oceanographic conditions are influenced by the Loop Current in the southeastern Gulf of Mexico, which merges with the Florida Current near the Dry Tortugas, and then flows eastward parallel to the barrier reef through the Straits of Florida (Figure 2). Depending on the prevailing oceanographic conditions and location, water quality in the Florida Keys can be dominated by near-field (e.g., sediment and nutrient loading from the Florida Keys) or far-field processes (e.g., Mississippi River inputs and SWFS runoff and harmful algal blooms).

Fish and Shellfish

The Florida Keys have more than 500 fish species, including 389 that are reef associated (Stark, 1968), and thousands of invertebrate species, including corals, sponges, shrimp, crabs, and lobsters. The fish and shellfish submodel includes the populations of fish and shellfish that are hunted by commercial and recreational fisheries or protected by management and the prey species required to support them. Populations of fish and shellfish move throughout the region of the Florida Keys and beyond. Most adults spawn on the barrier reefs and sometimes form large spawning aggregations (Domeier and Colin, 1997). The Dry Tortugas region, in particular, contains numerous known spawning aggregation sites (Schmidt *et al.,* 1999). Pelagic eggs and developing larvae are transported from spawning sites along the barrier reef tract by a combination of the Florida Current, eddies, and seasonal wind-driven currents and unique animal behaviors to eventually settle as early juveniles in a variety of inshore benthic habitats (Lee *et al.,* 1994; Ault *et al.,* 1999). As individuals develop from juveniles to adults, habitat utilization patterns generally shift from coastal bays to offshore reef environments.

Benthic Habitats

Benthic (bottom) habitats are distributed in a distinct order across the region from the Gulf of Mexico to the Atlantic (see Figure 6). Fringing mangrove habitats occur on the land-sea edge of coastal bays and around barrier islands. Coastal bays have three main benthic habitat types: seagrass beds, bare unconsolidated substrates, and oolitic limestone hardbottom populated with sponges and octocorals. Seaward of the Keys, benthic habitat types include stony coral patch reefs and barrier reefs, sponge-gorgonian covered hardbottom, seagrass beds, and carbonate sands. Each component of this mosaic provides critical habitat for different life stages of fish species in the snapper-grouper complex (Lindeman *et al.,* 2000). Some of the most important nursery habitats are located in coastal bays and near barrier islands (Lindeman *et al.,* 2000; Ault *et al.,* 2001).

Coral and Hardbottom

Reefs of the Florida Keys, from Key Biscayne to Key West, are commonly divided into two main types: offshore shelf-margin bank reefs and lagoonal patch reefs. Offshore bank reefs with spur and groove habitats are generally oriented perpendicular to the shelf and are found on the seaward face of the shelf-margin (Marszalek *et al.,* 1977). Patch reefs are high-relief features (up to 9 m of vertical relief) located within the inner lagoon between the Florida Keys and the shelf-margin reefs. Patch reefs are commonly dome- or linear-shaped and range in diameter from a few meters to up to 700 m (Marszalek *et al.,* 1977; Jaap, 1984; Lirman and Fong, 1997).

In addition to hermatypic, accreting reefs, low-relief hardbottom communities are a key component of the coastal habitats of South Florida (CSA International, Inc., 2009). Hardbottom habitats in the Florida Keys can be found adjacent to the mainland and islands at depths from less than 1 m to more than 20 m. Hardbottom communities are characterized by a limestone platform covered by a thin layer of sediment and consist of a sparse mixture of stony and soft corals, macroalgae, and sponges. Many 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 less than 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

There are few places on Earth where seagrass beds are as expansive as the nearshore marine ecosystem of South Florida, where there are at least 14,000 km^2 of seagrass beds (Fourqurean *et al.,* 2001). 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 (Zieman and Wetzel, 1980) and economically valuable (Costanza *et al.,* 1997) of ecosystems. The proximity of seagrass meadows to coral reef and mangrove ecosystems provides critical feeding grounds and nursery areas for species which rest on coral reefs or in mangroves as adults (Beck *et al.,* 2001). These associations are essential to maintaining the abundance of some coral reef and mangrove species (Valentine and Heck, 2005). This positive impact of seagrasses on coral reefs is in addition to the role that seagrasses play in protecting water quality on the coral reefs.

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 cannot be used by phytoplankton and macroalgae.

Mangroves

Prior to urbanization, there were 95,000 hectares (ha) of mangrove forests in the Florida Keys (Coastal Coordinating Council, 1974). Mangrove forests provide nursery habitat for numerous commercial fishery species and critical foraging habitat for adult fishes (Odum *et al.,* 1982; Lewis *et al.,* 1985; Faunce and Serafy, 2006). They also 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). Mangroves are highly effective at sequestering carbon dioxide, nutrients, and protecting 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 Florida Keys.

There are three species of mangroves in the Florida Keys: red (*Rhizophora mangle*), black (*Avicennia germanans*), and white (*Laguncularia recemosa*) mangroves. Buttonwood (*Conocarpus erectus*), a mangrove associate, is also common in mangrove forests in South 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 220 species of fish, 21 reptiles, 3 amphibians, 18 mammals, and 181 birds that utilize the mangroves of South Florida.

Ecosystem Services: What People Care About

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 Millennium Ecosystem Assessment project (cf., 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, freshwater, 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. All 12 *Ecosystem Services* are applicable to some degree within the FK/DT coastal marine ecosystem.

The primary importance of the ecosystem services that support recreation and tourism in the Florida Keys cannot be overstated. Approximately 70 percent of Keys residents regularly participate in water-based activities, such as fishing (48 percent), snorkeling (45 percent), beach activities (38 percent), and observing wildlife and nature (36 percent) (Leeworthy and Wiley, 1997). An equal number of people visit the Keys to engage in recreational activities. In 2007-2008, approximately 3.3 million visitor-trips were made to the Keys, totaling over 13.9 million person days; recreation was the purpose for 92 percent of these visits (Leeworthy *et al.,* 2010). In 2007-2008, about 53 percent of all visitors engaged in at least one water-based activity, such as snorkeling (22 percent), SCUBA diving (4.9 percent), fishing (12.9 percent), wildlife observation (19.9 percent), beach activities (27.6 percent), and sightseeing (45 percent) (Leeworthy *et al.* 2010). Tourism for recreation stimulated over $2.2 billion in local Keys production and supported over 32,000 local jobs (Leeworthy and Ehler, 2010a, 2010b).

Attributes People Care About: Linking State to Ecosystem Services

Most people will say they care about the clarity of the water column around the Florida Keys. The attribute of "clear water" directly relates to several environmental parameters that can be measured, such as secchi depth, and the light attenuation coefficient. Further, the notion of "clear water" also implies specific nutrient concentrations because nutrients control the potential for rapid growth of phytoplankton, leading to plankton blooms and murky water.

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. These are all readily measurable *State* attributes.

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 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 fishes of both the patch reef and seagrass communities, providing microhabitats for many juvenile fish. The three-dimensional structure provided by coral reefs provides another service—protection from the impacts of storm waves, surge, and tides—with respect to both natural shorelines and human property.

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

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.

column. Seagrass beds are also highly productive systems that 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 detrital food web provides food for various organisms.

People care about large numbers and a variety of species of birds that depend upon mangroves. Mangroves are also a component of the natural shoreline in the 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.

Valuing Ecosystem Services

Use and non-use values and avoided costs can be estimated and used in cost-benefit analyses of management actions deemed necessary to protect the quality of the environment. For example, the cost to improve wastewater and stormwater treatment in the Florida Keys is in the neighborhood of $1 billion. Leeworthy and Bowker (1997) quantified the total nonmarket use value, which is the use value net of the expenditures made to use all of the natural resources in the Keys, based on the benefits to tourists. Their study estimated the total asset value of the Keys' natural resources to range between $18.2 billion and $30.4 billion. Viewed in this way, the $1 billion price tag for improved wastewater treatment is small relative to the asset value of the natural resources that improved wastewater treatment will protect.

Economic values for ecosystem services from survey-based research were reported in the documents *Socioeconomic Study of Reefs in Southeast Florida* (Johns *et al.,* 2001) and *Socioeconomic Study of Reefs in Martin County, Florida* (Hazen and Sawyer, 2004). These studies provide estimates of the following values that represent the time period June 2000-May 2001 and Martin County from January 2003-December 2003: (1) total reef use of residents and visitors in each of the counties as measured in terms of 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 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 conditions; (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 billion in reef-related recreation expenditures and $330 million in willingness to pay to protect the reefs in their existing condition. 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. Southeast Florida coral and artificial reef-related recreation expenditures generated $4.4 billion in local production, $2 billion in resident income, and 70,000 jobs in the five-county area in 2001. 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 (see, for example, Hazen and Sawyer, 2008).

Response: Taking Action

The coastal marine ecosystem that exists today surrounding the Florida Keys differs markedly from what existed 40 years ago. The human population of the Keys is much larger today, although it is stable. As a consequence, there has been 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. 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 (e.g., more boats and the potential for impacts to seafloor corals and seagrasses). 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.

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 of control.

Controls on Development

In 1975, growing recognition that booming development posed a threat to the unique environment of the Florida Keys led the State of Florida government to designate the Keys as an "Area of Critical Concern." This designation brought planning and development activities in Monroe County under the control of the Florida Department of Community Affairs (FDCA) with the overall goal:

> *"…to conserve and protect the natural, environmental, historical, and economic resources; the scenic beauty; and the public facilities within the Area of Critical Concern."*

Monroe County was eventually required to adopt a Rate of Growth Ordinance in 1992 that drastically reduced the pace of new development while, at the same time, encouraged replacement of ineffective cesspits by septic systems and preservation of natural habitat. More recently, the FDCA and Monroe County undertook a comprehensive study of the ecological carrying capacity in the Keys, with mixed results (National Research Council, 2002). Historically, development in the Keys relied on on-site cesspits and septic tanks, which resulted in water quality degradation of inshore areas. Monroe County is currently implementing a comprehensive plan to install centralized sewage treatment in densely-populated areas of the Keys. The plan includes measures such as new criteria for on-site sewage treatment and disposal systems and connection of individual homes and subdivisions to county wastewater treatment plants.

This *Response* by agencies has had demonstrable effects on *Drivers, Pressures*, and the *State* of the marine environment. The rate of growth ordinance adopted in 1992 has drastically reduced the rate of population growth in the Keys, even as the population of the South Florida region (Broward, Collier, Miami-Dade, Monroe, and Palm Beach counties) continued at a rapid expansion. The historic and forecasted population of South Florida is compared to that of Monroe County in Figure 8.

Protected Areas

The designation of protected areas is one way of controlling *Pressures* with human activities in the ecosystem. Protection can be used to restrict a variety of different human activities. For example, in 1985 the Florida Keys were designated as Outstanding Florida Waters, which established a high standard for the protection of water quality. In 2002, the Florida Keys were designated as a No Discharge Zone, which prohibits the discharge of boater sewage into all state waters of the FKNMS.

Florida Keys National Marine Sanctuary and Protection Act

Responding to concerns about the health and ecological future of the coral reefs in the Florida Keys, the U.S. Congress acted in 1990 to immediately address two major concerns of Keys residents by prohibiting drilling and exploration

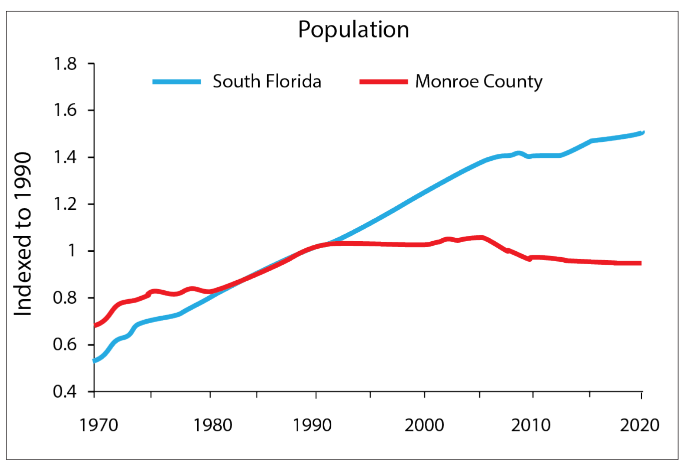

Figure 8. Human population in the Florida Keys, a local *Driver,* stopped its upward trend soon after 1990, even as the population in South Florida as a whole has continued to grow (Data sources: population http://edr.state.fl.us/population.htm).

for oil and minerals in Keys waters and by excluding large vessels (>50 m in length) from these waters. The Act (http://floridakeys.noaa.gov/about/fknmsp_act.html) also provided for long-term management by establishing the FKNMS (Figure 9) with the goals:

> *"To achieve the protection and preservation of living and other resources of the Florida Keys marine environment."*

In particular, the Act mandated the FKNMS program to "consider temporal and geographic zoning to ensure protection of sanctuary resources." Since its inception, the FKNMS program and its local partners have initiated a number of different *Response* activities, including:

- Reducing or eliminating waste discharge to marine waters from boaters;
- Developing and implementing an infrastructure-based, rather than a standards-based, strategy for stormwater and wastewater management in the Keys;
- Organizing a Keys-wide volunteer program;
- Developing and implementing a research and monitoring program that supports a science-based approach to dealing with environmental issues;
- Restoring damages caused by vessel groundings;
- Protecting unique maritime heritage resources;

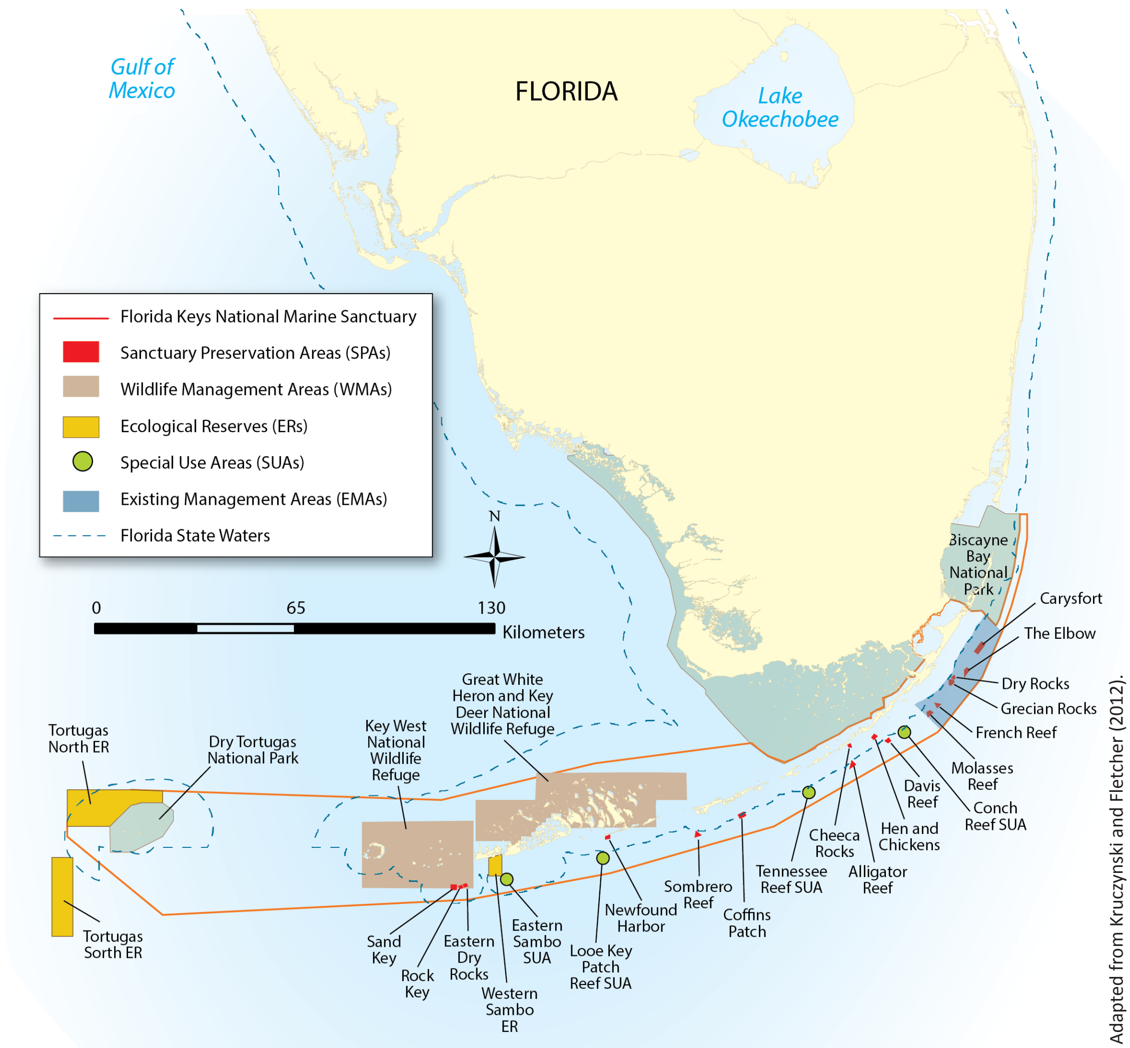

Figure 9. The Florida Keys National Marine Sanctuary was established by Congress in 1990 to protect more than 2900 square nautical miles of Florida Keys coastal and ocean waters.

- Installing mooring buoys to eliminate damage to benthic communities from boat anchors and to help enforce regulations on visitor use of marine resources; and
- Installing channel markers to improve navigation and reduce groundings.

Dry Tortugas National Park

Surrounded by the FKNMS, Dry Tortugas National Park encompasses seven small islands, the Dry Tortugas, at the extreme western end of the Florida Keys, along the Straits of Florida. The park consists almost entirely (99.8 percent) of shallow water marine ecosystems. The U.S. Congress authorized the park in 1992 to "preserve and protect for the education, inspiration, and enjoyment of present and future generations [these] nationally significant natural, historic, scenic, marine, and scientific values in south Florida." The enabling legislation stipulated that the park must be managed so as to protect, among other values, "a pristine subtropical marine ecosystem, including an intact coral reef community."

State Parks and Federal Refuges

In support of these objectives, several agencies cooperatively manage an area around the Dry Tortugas as an ecological reserve and Research Natural Area (RNA). The National Park Service (NPS) manages the RNA of the park, which was created by NPS special regulation in 2006 and provides a no-fishing and no-anchoring zone that is contiguous with the Tortugas Ecological Reserve of the FKNMS established by the National Oceanic and Atmospheric Administration and the State of Florida. A complex legal history gives both the NPS and the Florida Fish and Wildlife Conservation Commission responsibilities for the management of natural resources within the RNA. The establishment of federal/state agreements which guide both research and management activities within the RNA has resolved these complexities. Together, the RNA and the larger Tortugas Ecological Reserve help to ensure the successful management of both marine and terrestrial ecosystems while offering outstanding opportunities for scientific research and public education.

Ecosystem Research and Monitoring

In 2007, Dry Tortugas National Park and the Florida Fish and Wildlife Commission established a program of ecosystem research and monitoring designed to evaluate the efficacy of marine protected areas as a conservation tool. In implementing zoning regulations, as charged by Congress, the FKNMS has established a number of marine protected areas. The intent is that protection of these refuges from exploitation by fishing will promote the recovery of fish populations impacted by overfishing. However, the original intent in establishing most of the marine protected areas, especially the Sanctuary Preservation Areas, primarily was to resolve conflicts between user groups, not as refugia for fish.

This research program operates within the Dry Tortugas National Park RNA, established as for the program with the goal to:

> *"Protect near pristine shallow water marine habitat, ensure species diversity, enhance the productivity and sustainability of exploited fish populations throughout the region, and provide a unique unexploited area that will be used to help assess the effects of fishing on exploited area."*

Southeast Florida Regional Climate Change Compact

In *Response* to the relatively new threat of climate change, Monroe County joined with Miami-Dade, Broward, and Palm Beach counties 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 toward 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 10 (Southeast Florida Regional Climate Change Compact, 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

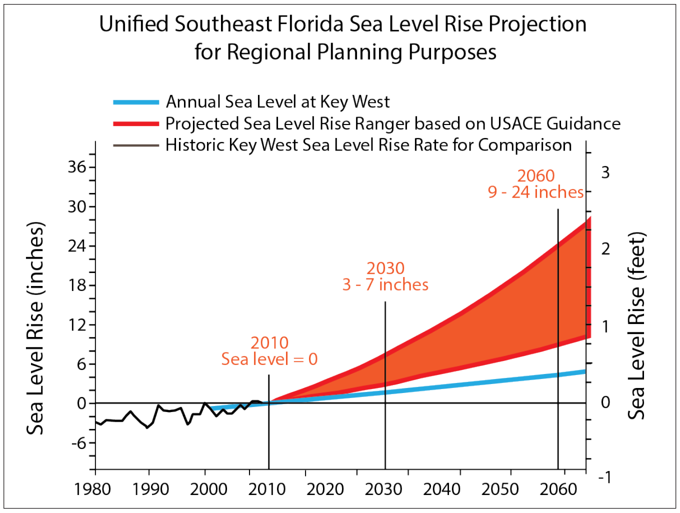

Figure 10. Unified southeast Florida sea-level rise projection for regional planning (Southeast Florida Regional Climate Change Compact, 2011; calculations courtesy of K. Esterson, U.S. Army Corps of Engineers).

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 10). 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 2-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.

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Water Column

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In a nutshell:

- The diverse habitats and living marine resources within the Florida Keys marine ecosystem rely upon oligotrophic conditions (low nutrient and phytoplankton concentrations) to exist and thrive.
- People value the oligotrophic conditions because they result in clear water for diving and fishing; few toxins and pathogens lead to good quality seafood, fisheries, and beaches.
- Small increases in nutrients and/or decreases in grazers can produce dramatic, ecologically-detrimental results, such as macroalgal overgrowth on coral reefs and phytoplankton blooms. The major threat to the Florida Keys water column is increased nutrient loading from local terrestrial sources in the nearshore and far-field sources in the offshore and/or the loss of grazers due to human manipulations including the harvest of grazer species.

The water column is defined as the physical, chemical, and biological characteristics of the water column, including suspended benthic sediment, phytoplankton, and zooplankton. It encompasses all aspects of water quality, in addition to zooplankton and physical properties (e.g., temperature and salinity, etc.). It does not include benthic organisms that are incorporated into the hardbottom and seagrass submodels or fauna not captured by standard plankton nets. These fauna are incorporated into the fisheries or protected species submodels. All other aspects of the ecosystem rely upon the biological, chemical, and physical habitat traits encompassed in the water column submodel.

Maintaining oligotrophic conditions is essential to sustain the key characteristics that make the Florida Keys a desirable ecosystem for tourism.

The water column in the Florida Keys marine ecosystem is characterized by persistent, widespread oligotrophic conditions. The primary characteristic of an oligotrophic ecosystem is very low nutrient concentrations. In the Florida Keys, low nutrient concentrations result in low phytoplankton and organic matter concentrations with high water clarity and dissolved oxygen concentrations. If nutrient concentrations increase, it is likely that phytoplankton (Boyer *et al.,* 2009), benthic macroalgae (Duarte, 1995;

Valiela *et al.,* 1997), and harmful algal bloom frequency will increase (Brand and Compton, 2007). Depending on the prevailing oceanographic conditions and location, nutrient sources in the Florida Keys are dominated by near-field (e.g., sediment and nutrient loading from the Florida Keys) or far-field processes (e.g., Mississippi River and Southwest Florida Shelf runoff).

Increases in nutrient loading from either area will result in more phytoplankton blooms and decreased water clarity in the Florida Keys. This is a concern because water clarity is already lower in the Florida Keys than other Caribbean locations (Palandro *et al.,* 2004). Moreover, the Florida Keys marine ecosystem must remain oligotrophic to support the highly valuable and characteristic benthic habitats, such as seagrass beds, sponges, and coral reefs.

Role in Ecosystem: The Water Column Supports Fisheries and Their Habitat

The Florida Keys marine ecosystem is currently dominated by benthic productivity. Healthy seagrass beds, coral reefs, and hardbottom provide vital habitat for many commercial fishery species (Luo *et al.,* 2009). If pelagic primary productivity (i.e., phytoplankton blooms) begins to dominate, there is likely to be numerous detrimental effects on fish and shellfish, as well as the benthic habitat communities. The most prominent supporting service provided by the water column to benthic habitats (coral and hardbottom and seagrass submodels) is good water clarity, allowing sufficient light to reach the benthos and provide energy to the benthic primary producers. Corals require sufficient light to provide maximize growth rates (Cooper *et al.,* 2009). However, too much light on the coral reefs can cause ultraviolet stress and lead to coral bleaching (Glynn, 1993). Seagrass require greater than 10 percent of surface irradiance to reach the benthos (Duarte, 1991). Thus, increasing the magnitude of phytoplankton blooms will decrease light availability at the benthos and could lead to seagrass die-offs. These die-offs lead to the development of a positive feedback loop. Seagrass die-offs release nutrients as their leaves decay and destabilize sediments, leading to increased nutrient resuspension (Zieman *et al.,* 1999), and the loss of sponges decreases the grazing pressure on phytoplankton (Lynch and Phlips, 2000). The increase in nutrients and decrease in grazing help to maintain and may intensify the phytoplankton blooms.

The water column supports fisheries through previously mentioned habitat-supporting services and directly by providing the base of the food web and a potential pathway for pathogens and toxins. The loss of benthic habitat results in a decrease in commercial fishery populations, as was seen when the lobster population decreased after a *Synechococcus* bloom caused a sponge die-off (Butler *et al.,* 1995). However, phytoplankton also provide food for zooplankton which, in turn, are consumed by higher trophic level fish and shellfish species (Harris *et al.,* 2000). Grazer biomass is tightly coupled to phytoplankton biomass, and phytoplankton can both limit and be limited by grazer biomass. However, phytoplankton species have different sizes and nutritional characteristics (Hitchcock, 1982). Thus, the species of phytoplankton present significantly affects the efficiency of trophic transfers and the amount of energy available to upper trophic levels (Richardson *et al.,* 2003). Moreover, zooplankton grazing upon some harmful algal species can accumulate toxins and cause fish kills (White, 1981).

Attributes People Care About

The Florida Keys water column supports attributes of the Florida Keys marine environment that people care about (Figure 1). These attributes are directly related to ecosystem services provided by the Florida Keys marine ecosystem:

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

Harmful Algal Blooms

Harmful algal blooms are a naturally-occurring part of the Florida Keys but, in recent years, debate has intensified as to whether anthropogenic activities are increasing their frequency and duration. A recent metadata review suggested

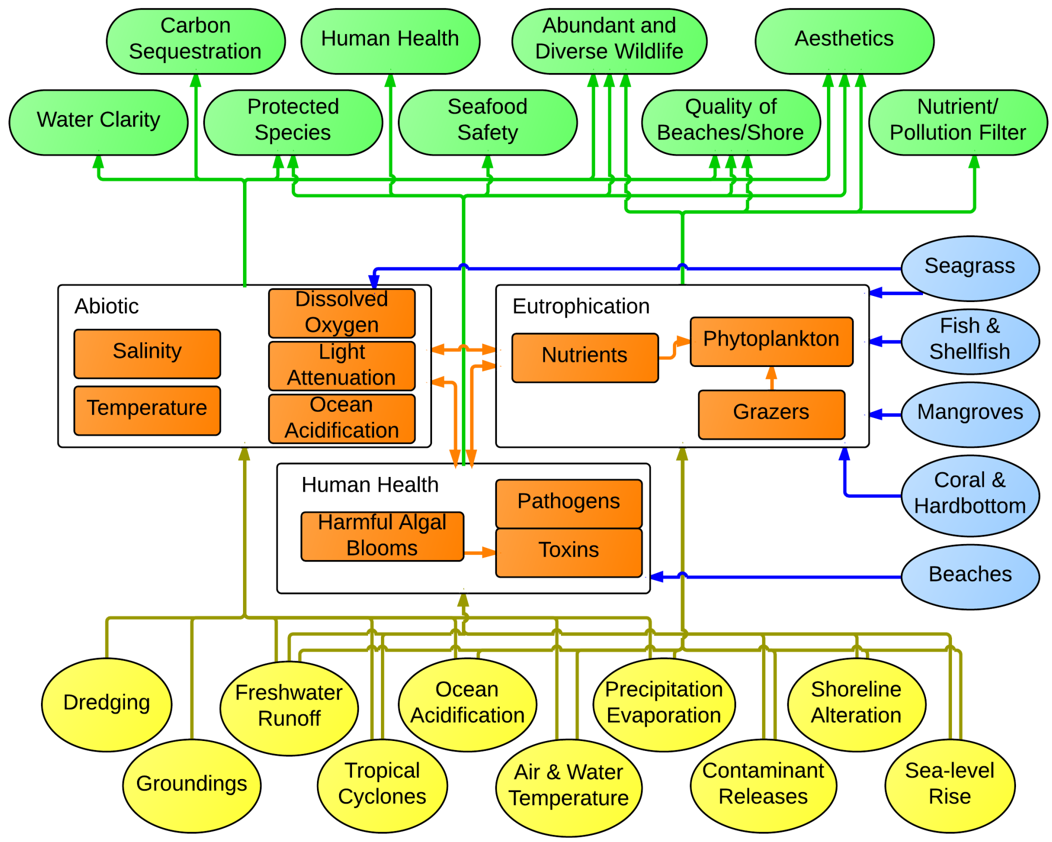

Figure 1. Water column submodel diagram for the Florida Keys/Dry Tortugas.

that increases in harmful algal blooms along southwest Florida are related to increased nutrient availability (Brand and Compton, 2007). Harmful algal blooms in the Florida Keys are primarily composed of the dinoflagellate, *Karenia brevis*. Moreover, large blooms of *K. brevis* result in hypoxic conditions (low dissolved oxygen) under specific oceanographic conditions (Hu *et al.,* 2006).

Water Clarity

The clarity of the water is a direct product of light attenuation and is dependent upon the concentrations of chromophoric dissolved organic matter (CDOM), phytoplankton, and suspended particulate matter. The diving and fishing industries rely upon good water clarity to ensure business remains optimal. Water clarity is already lower in the Florida Keys than in other Caribbean locations, and further degradation should be prevented (Palandro *et al.,* 2004).

Quality of Beaches and Shoreline

The quality of beaches and the shoreline of the Florida Keys is important to tourists and residents. One of the appealing features of the Florida Keys is the impressive color mosaics one can view when driving on the Overseas Highway or sailing along in a boat. Moreover, water sports are one of the main reasons for visiting and living in the Florida Keys. The quality of the shoreline, beaches, and water is measured in terms of aesthetics and the likelihood of contracting a health problem.

Aesthetics can be impacted by the health of nearby seagrass beds, suspended particulate matter, and phytoplankton blooms. Threats to beach and shoreline quality include air quality and water quality concerns. The two primary causes of poor air quality are harmful algal blooms and hypoxia. The hypoxia concern is particularly unpleasant in man-made canals that turn over during high winds, causing a hydrogen sulfide (rotten egg) odor to be released. The dominant harmful algal bloom species in the Keys, *K. brevis*, contains a brevetoxin compound that can aerate and cause respiratory distress (Fleming *et al.,* 2011).

Protected Species

One of the many reasons tourists and residents enjoy the Florida Keys is the ample opportunity to view charismatic megafauna that inhabit the ecosystem. These range from reptiles, such as sea turtles, to fish, such as marlins, to marine mammals, such as manatees and dolphins. These animals are most sensitive to toxins from chemicals that tend to bioaccumulate up the food chain. Dolphins have been found to have high levels of polychlorinated biphenyls (PCBs) in nearby embayments (Litz *et al.,* 2007), and high mercury levels have been observed in large fish species within Florida Bay (Evans and Crumley, 2005). Dolphin mortality has been associated with high brevetoxin concentrations and harmful algal blooms along the southwest coast of Florida (Fire *et al.,* 2008; de la Riva *et al.,* 2009). Loggerhead turtles, *Caretta caretta*, in South Florida have been found with a neurological disorder that suggests lethal toxin levels in their diet (Jacobson *et al.,* 2006). The red-tide neurotoxin has been reported to have a high affinity for binding to specific nerve preparations in manatee brains, likely increasing strandings and mortality in affected populations (Trainer and Baden, 1999). The red-tide neurotoxin has also been implicated in degraded health in whale species known to migrate through the Florida Keys (Doucette *et al.,* 2006). These species are also dependent upon the seagrass for habitat and, in the case of manatees and sea turtles, for food.

Seafood Safety

The safe consumption of seafood from the Florida Keys is necessary to maintain the economic health of the fisheries. Harmful algal blooms can cause shellfish, including oysters, to be unsafe for consumption and leave humans susceptible to paralytic shellfish poisoning (Kirkpatrick *et al.,* 2004). Toxin loading in the form of mercury can endanger the consumption of higher trophic level fish species (Plessi *et al.,* 2001). This attribute is equally important for residents and tourists, but also for anyone who consumes seafood from the Florida Keys.

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). These fisheries rely on energy in the form of their prey base, which ultimately derive their energy from primary producers, many of which are the phytoplankton located within the water column. The right concentration and species composition of primary producers is necessary to have the productive fisheries in the Florida Keys that we have grown accustomed to having.

Quantifiable Attributes

There are several monitoring programs of varying scope being conducted to assess the water column of the Florida Keys. The Florida International University's Southeast Environmental Research Center (FIU/SERC, http://serc.fiu.edu/wqmnetwork/) and NOAA's Atlantic Oceanographic and Meteorological Laboratory (NOAA/AOML, http://www.aoml.noaa.gov/sfp) conduct the two programs with the longest records and greatest spatial coverage. Both programs aim to assess long-term trends of water quality and potential eutrophication in the Florida Keys through the systematic measurement of water column parameters. However, there are some key differences. The NOAA/AOML program focuses on producing synoptic spatial maps of key parameters for the entire South Florida coastal ecosystem, whereas FIU/SERC focuses on the measurement of more nutrient parameters at each station. The NOAA/AOML program also has a physical oceanographic focus and conducts regular current measurements and drifter deployments. While these monitoring programs are essential, they are not optimal due to funding realities. Thus, they are insufficient to provide a comprehensive understanding of the complex dynamics within the Florida Keys water column.

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

- Nutrients
- Chromophoric dissolved organic matter (CDOM)
- Suspended particulate matter
- Phytoplankton blooms
- Dissolved oxygen
- Salinity
- Pathogens and toxins
- Grazers

Nutrients

The oligotrophic nature of the Florida Keys allows corals, seagrasses, and hardbottom communities to thrive and clear water to dominate. Nutrient concentrations are likely to change in response to changes in nutrient loading or nutrient cycling caused by land-use changes. If nutrient concentrations increase, it is likely that phytoplankton (Boyer *et al.,* 2009), benthic macroalgae (Duarte, 1995; Valiela *et al.,* 1997), and harmful algal bloom frequency will increase (Brand and Compton, 2007). This could damage the key characteristics that make the Florida Keys a desirable ecosystem for tourism.

Chromophoric Dissolved Organic Matter

Chromophoric dissolved organic matter is primarily derived from terrigenous sources; however, in South Florida there can also be a significant component produced in the marine environment (Milbrandt *et al.,* 2010). Chromophoric dissolved organic matter contributes to light attenuation (Kelble *et al.,* 2005).

Suspended Particulate Matter

Concentrations of suspended particulate matter in the water column affect light attenuation and thus water clarity in the Florida Keys (Kelble *et al.,* 2005). The effect on light attenuation is likely to be important given that the light field of nearby ecosystems is dominated by suspended particulate matter (Kelble *et al.,* 2005). This concentration is affected by sediment loading from the terrestrial system that has been altered by land-use changes (Wood and Armitage, 1997). Benthic vegetation also alters the concentration of suspended sediment in the Florida Keys by stabilizing benthic sediments and minimizing resuspension (Peterson *et al.,* 2002). Suspended particulate matter can also clog filter feeders, particularly sponges, causing an increase in phytoplankton blooms. Depending on sediment type, however, these species may also be able to filter suspended sediments out of the water column (Lohrer *et al.,* 2006).

Phytoplankton Blooms

Phytoplankton are single-celled photoautotrophic plankton. They consist of a wide variety of taxa, including both prokaryotes and eukaryotes. They form the base of the pelagic food web. Thus, the ecosystem requires low levels of the right types of phytoplankton to maintain the proper productivity necessary to support higher trophic level species. However, too much phytoplankton will discolor the water, causing light attenuation to decrease (Phlips *et al.,* 1995). The biomass of phytoplankton in the water column is, to a large degree, dependent upon nutrient concentrations and water temperature that may be altered by climate change. High phytoplankton biomass has the potential to cause senescence in seagrass and sponges due to insufficient light at the benthos, and clogging, respectively (Butler *et al.,* 1995). These changes increase phytoplankton concentration by decreasing the grazing pressure and increasing the nutrient loading from the benthos by destabilizing sediments (Zieman *et al.,* 1999).

Harmful algal blooms are a type of phytoplankton bloom and a naturally-occurring part of the Florida Keys. Harmful algal blooms are not initiated in the Florida Keys. Instead, they are advected into the Florida Keys after their initiation on the Southwest Florida Shelf. Harmful algal blooms in the Florida Keys are primarily composed of the dinoflagellate, *K. brevis*. *K brevis* 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). Moreover, large blooms of *K. brevis* result in hypoxic conditions (low dissolved oxygen) under specific oceanographic conditions (Hu *et al.,* 2006).

Dissolved Oxygen

Hypoxia is a state of low oxygen levels in the water column. It typically occurs when a large amount of plant material is consumed or decomposed by bacteria or other organisms that are not readily available to the next trophic level. Thus, phytoplankton blooms alter dissolved oxygen by producing oxygen during photosynthesis; however, blooms composed of phytoplankton types that are not easily consumed by secondary producers can lower dissolved oxygen at the benthos when phytoplankton senesce and are decomposed (Turner *et al.,* 2006). These hypoxia events typically occur when stratification is present such that the oxygen produced by primary production is not readily mixed with the hypoxic waters (Livingston, 2007). Dissolved oxygen concentrations are significantly affected by benthic vegetation that produce oxygen during the day and consume oxygen at night (Yarbro and Carlson, 2008). Low dissolved oxygen concentrations can lead to air quality concerns. In particular, hypoxia can create an undesirable odor from the production of hydrogen sulfide by decomposers. This is most prominent when a stratified water column is turned over. Hypoxia can also affect the health of fish, dolphins, sea turtles, manatees, and whales by restricting their habitat and influencing the size of prey populations (Zhang *et al.,* 2009).

Salinity

Maintaining the appropriate salinities in the water column of the Florida Keys is essential for ecosystem health and to sustain the species assemblage characteristic of the Florida Keys. Many fish species are found in a wide range of salinities, but nearly all have optimal salinities at which they thrive (Serrano *et al.,* 2007; Serrano *et al.,* 2010). Salinity concentrations are a product of the prior salinity and the net freshwater supply, which is precipitation plus runoff minus evaporation (Kelble *et al.,* 2007). Within the Florida Keys, salinity is typically near oceanographic values of 36.4; however, nearshore salinities are much lower due to the influence of runoff. Salinity can also be affected by far-field runoff from sources such as the Mississippi River (Ortner *et al.,* 1995).

Pathogens and Toxins

Pathogen and toxin concentrations in the ecosystem affect both ecological and human health. Pathogens are microrganisms that cause disease either directly or indirectly through the production of toxins. Toxins are chemical compounds that negatively affect human and organismal health. Contaminant spills (Moore and Swain, 1991), harmful algal blooms (Kirkpatrick *et al.,* 2004), toxin loading, and changing land-use patterns (Paul and Meyer, 2001) all alter pathogen and toxin concentrations in the water. Specifically, increasing the percent of impermeable surface area on the land increases the loading of toxins to coastal systems (Paul and Meyer, 2001). Marine species such as fish, manatees, sea turtles, whales, and dolphins exhibit degraded health and increased mortality in the presence of high toxin concentrations. Toxins degrade air quality and can cause respiratory distress in humans (Kirkpatrick *et al.,* 2004). Moreover, consumption of seafood with high toxin levels can cause paralytic shellfish poisoning, gastrointestinal distress, and developmental disorders (Stewart, 2008; Kirkpatrick *et al.,* 2010). Swimming in water with high pathogen and toxin levels can also negatively impact human health (Abdelzaher *et al.,* 2011).

Grazers

Grazers play a crucial role in ecosystems via consumption of phytoplankton that minimize blooms and transfer energy to higher trophic levels. Grazers can take many forms from benthic sponges and shellfish to microscopic zooplankton to parrotfish. For more detail on benthic grazers, please consult the coral and hardbottom submodel and, for fish species, please consult the fish submodel. Zooplankton provide a key pathway from phytoplankton to higher trophic level fish and shellfish species (Harris *et al.,* 2000). Grazer biomass is tightly coupled to phytoplankton biomass, and phytoplankton can both limit and be limited by grazer biomass. Grazers, zooplankton in particular, are also governed by kinetics and thus show a large temperature influence that may be altered by climate change (Huntley and Lopez, 1992). Grazers also consume oxygen and thus decrease the dissolved oxygen concentration.

Drivers of Change in the Florida Keys Water Column

Changes to the Florida Keys water column stem from both near-field and far-field pressures. These pressures can be both natural and anthropogenic; however, henceforth we will focus on anthropogenic pressures because they respond to management actions. Although drivers can be delineated into near- and far-field, they all share the same ultimate driver of human population and its demands. Interestingly, human population growth has slowed in the Florida Keys and has even stabilized in recent years, while the global population has continued to experience exponential growth. The human population and civilization attempt to meet demands for food, water, and shelter, as well as energy, recreation, and economic growth. Meeting these demands both within the Florida Keys and beyond results in pressures on the Florida Keys marine ecosystem.

To meet food demands requires agriculture and fisheries in South Florida, as well as increased shipping to import foods grown in other regions. This means altered land-use and altered freshwater quantity, quality, timing, and distribution (QQTD) for agriculture to thrive and increased dredging and altered shoreline to support shipping. The alteration of freshwater QQTD in South Florida has also been undertaken to meet freshwater demand and increase the area of habitable land for humans. The shoreline will also be altered to meet shelter demands of both tourists and residents and, to meet these shelter demands, also requires increased disposal of wastewater and thus a likely increase in wastewater discharge. Energy demands in the Florida Keys are currently met by burning fossil fuels within the Florida Keys or importing energy produced elsewhere. These practices are increasing CO_2 in the atmosphere, which increases ocean acidification and causes changes to climate (IPCC, 2007). In addition, there are environmental impacts from marine exploration and extraction of hydrocarbons. Although this is not currently performed in the Florida Keys, upstream activities in the Gulf of Mexico and off the northern coast of Cuba can impact the Florida Keys marine water column. Most recreational activities in the Florida Keys occur in or adjacent to the marine environment through boating, fishing, diving, and visiting beaches. Boating has many of the same impacts as shipping in the form of dredging, altered shoreline, groundings, and increased contaminant spills at marinas. Diving requires boating in many cases and thus shares these pressures. Going to beaches places pressures on the water column largely through toxin and pathogen loading from beaches to the marine ecosystem.

Fisheries

Fisheries, both recreational and commercial, systematically remove large-bodied top predators from the ecosystem, drastically altering the food web (Jackson, 2001; Jackson *et al.,* 2001; Myers and Worm, 2003). 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). These fishery impacts are primarily near-field and subject to management controls.

Freshwater QQTD

To meet freshwater requirements and drain land to make it more habitable for humans, we have drastically altered the QQTD in South Florida (Light and Dineen, 1994). The decrease in runoff may be 60 percent or greater in some areas of South Florida (Smith *et al.,* 1989; Marshall *et al.,*2009). These changes in runoff patterns result in salinity alterations, but also change all parameters that are transported into the marine environment through freshwater runoff. The system is especially sensitive to increases in nutrients because it is an oligotrophic system. Thus, minimizing nutrient loading is critical to maintain the health of this system (Collado-Vides *et al.*, 2007).

Altered Land Use and Shoreline

Changing land use to meet human demands is an important process that can have ecological implications for the Florida Keys. The development of agricultural lands in the watershed can result in increased loading of nutrients, chromophoric dissolved organic matter, and toxins if not properly managed. Removal of mangrove forests and other plants that stabilize sediments can cause increases in suspended sediment. The development of high-density population structures can affect nutrient levels, toxin levels, and suspended sediment. Specifically, increasing the percent of impermeable surface area on the land increases the loading of toxins to coastal systems (Paul and Meyer, 2001). Agricultural activities on the Florida peninsula may also affect the Florida Keys water column when runoff from these lands is advected into the Florida Keys (Lapointe *et al.,*2004).

Wastewater Discharge

The discharge of wastewater into the Florida Keys marine environment would likely be due to non-point source contamination through the leaching of injection wells or septic systems. Evidence has already been found that the direct injection wells load viral contaminants into the nearshore (Paul *et al.,* 1997). In addition to pathogen loading, wastewater discharge may load nutrients. On the northern section of the Florida reef tract, wastewater discharge has been found to increase nitrogen loading and cause macroalgal overgrowth of coral reefs (Lapointe, 1997).

Climate Change

The emission of greenhouse gases, including CO_2, provides a double dose of stress to the Florida Keys ecosystem. First, the increase in CO_2 concentrations is causing a decrease in the aragonite saturation state of seawater and lowering the pH, which is commonly referred to as ocean acidification. This decrease can have detrimental effects on calcifying organisms, including the coral reefs of the Florida Keys (Manzello *et al.,* 2008). 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 over several generations allowing organisms to adapt (Hendriks *et al.,* 2010). Secondly, according to the IPCC (2007) report, the increase in CO_2 is likely resulting in warmer ocean temperatures and changing rainfall patterns. These changes to rainfall and temperature will affect the health of organisms living in the water column.

Mechanisms of Change

The primary mechanisms by which these drivers bring about change in the Florida Keys water column is through phytoplankton blooms, a loss of grazers, disease, and organismal physiology.

Phytoplankton Blooms/Nutrient Loading

In addition to reducing water clarity, increased eutrophication associated with increased nutrient concentrations can negatively impact benthic habitats through overgrowth by less desirable macroalgae. Recent investigations of Florida Keys coral reefs have observed an increase in diversity and abundance of macroalgae, possibly as a result of anthropogenic nutrient loading (Lapointe *et al.,* 2004). Macroalgae are detrimental to the health of the corals and are not as aesthetically pleasing to divers. A healthy seagrass community is a byproduct of good water quality and natural nutrient concentrations. Seagrass beds in the Florida Keys have been observed to increase macroalgal abundance in correlation with increased nitrogen concentrations (Collado-Vides *et al.,* 2007).

Increasing nutrient concentrations will also likely increase phytoplankton concentrations and favor more ecologically damaging phytoplankton species (Livingston, 2007; Boyer *et al.,* 2009). In adjacent waters, blooms of picoplanktonic *Synechococcus* have occurred after increased nutrient loading (Rudnick *et al.,* 2007). These *Synechococcus* blooms have been implicated as the causative agent in a cascade of ecological disturbances that included a massive loss of sponge populations. These blooms have also coincided with hypoxic conditions (Madden and McDonald, 2009), which affect the health of fisheries, dolphins, sea turtles, manatees, and whales by restricting their habitat and influencing the size of prey populations (Zhang *et al.,* 2009).

Although phytoplankton blooms are a natural phenomenon in some upstream waters of the Florida Keys, increased nutrient loading by altering freshwater QQTD and land-use changes can increase the frequency, magnitude, duration, and spatial extent of phytoplankton blooms. These increases can lead to blooms being advected into the Florida Keys and potentially damaging the ecosystem and reducing the quantity and quality of ecosystem services. As mentioned, an increase in phytoplankton blooms negatively impacts all other aspects of the marine ecosystem and likely poses the most immediate, severe threat to the Florida Keys water column.

Loss of Grazers—Food Web alterations

As discussed in the fisheries driver, removing the largest of marine predators causes food web changes that can ultimately decrease grazing upon phytoplankton (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).

Disease

Disease to both humans and marine life as a result of increased pathogen and toxin concentrations in the water column could be a major source of degradation to the Florida Keys water column. In fact, it is not even the incidence of disease as much as the perception that the water is safe for swimming, diving, and consumption of its marine life.

Physiology

Changing the 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 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 the Florida Keys are already living near their thermal maximums (Manzello *et al.,* 2007).

Status and Trends

The FIU/SERC data has been extensively examined for trends (Boyer and Briceno, 2010). There were several trends that were consistent throughout the Florida Keys from the Dry Tortugas to northern Key Largo. Total organic carbon had a consistent decreasing trend throughout the Florida Keys. Salinity had a consistent increasing trend that was more pronounced on the northern edge of the Keys in the back country and sluiceway (Figure 2). This increase in salinity could affect physiology because most organisms do not prefer salinities greater than the adjacent coastal ocean (Serrano *et al.,* 2010).

Trends in nutrient and chlorophyll-a concentrations, likely indicators of eutrophication (Boyer *et al.,* 2009), are less clear. Chlorophyll-a had no significant increases and, in fact, had significant decreases in many areas of the Florida Keys, particularly on the oceanside. However, total phosphorus, the limiting nutrient to phytoplankton in some adjacent systems (Fourqurean *et al.,* 1993; Boyer *et al.,* 1997), was increasing in most of the Florida Keys, and dissolved inorganic nitrogen, another potentially limiting nutrient (Lapointe, 1997), had no net clear trend as NO_3 decreased and NH_4 increased. These may indicate the increase in total phosphorus is localized and not affecting phytoplankton biomass. However, dissolved oxygen was generally decreasing, especially in the back country and sluiceway, which is a typical response to eutrophication. If concentrations drop low enough, the result is unfavorable habitat conditions for many organisms.

Figure 2. Map of sluiceway and back country (Florida Bay).

There was also a net decrease in light attenuation, which reflects an increase in water clarity. This is beneficial to benthic primary producers because it means more light is reaching the benthos and providing more energy for benthic primary producers. It is also beneficial for ecosystem services, as most divers and many fishermen prefer or require clear water to effectively conduct their activity.

Topics of Scientific Debate and Uncertainty

A primary research need is understanding how altered nutrient loading affects water quality and thus habitats and fish. Specifically, understanding the impact of human development on the ecosystem needs to be quantified. Replacing one square mile of pristine coastline with impermeable developed land has negative impacts on water quality, but there is a need to better quantify this impact 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. Accurate quantification of nutrient and toxin loading from septic tanks would allow managers to decide whether conversion to sewer systems would significantly improve water quality prior to implementing this action.

Another primary research need is to develop an understanding of the causes of shifts in phytoplankton communities. There is significant research on the factors that determine phytoplankton type in the open ocean, but much less for coastal waters such as the Florida Keys. The type of phytoplankton that dominates the system affects the entire trophic web. Small, cyanobacterial phytoplankton support fewer large zooplankton and thus less energy is available to fish populations. Moreover, cyanobacteria can "clog" sponges and cause them to senesce (Phlips *et al.,* 1999). This loss of hardbottom habitat triggers a cascade of negative ecological effects that affect the commercially important Caribbean spiny lobster among other species (Butler *et al.,* 1995). Improved research should focus on being able to determine the factors that lead to a dominance of cyanobacteria over other phytoplankton types. This would allow managers to actively try to avoid these conditions and thus maintain a healthier phytoplankton community.

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Fish and Shellfish

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In a nutshell

- Fish and shellfish in the Florida Keys support commercial and recreational fisheries, help to control the overgrowth of macroalgae on the coral reef, and connect the Florida Keys with other reef ecosystems in the Caribbean region.
- A large part of the Keys economy is supported by people traveling into the region for recreational fishing and for viewing the diversity of marine species through diving and other activities.
- Populations of reef fish have been overfished in the past, and present populations still show signs of the effects of unsustainable overfishing.
- Fish and shellfish populations in the region are vulnerable to changes in critical habitats expected as the result of climate change and the cumulative impact of human activities on coastal marine waters.

Definition of the Resource

The waters surrounding the Florida Keys and Dry Tortugas (FK/DT) coral reef ecosystem contain a diversity of marine life. The goods and services provided by this ecosystem extend beyond fishing to include a range of educational, scientific, aesthetic, and other recreational uses, such as snorkeling, SCUBA diving, and tourism (Ault *et al.,* 2005a). Over 500 species of fish are found here, including more than 389 that are reef associated (Stark, 1968), and thousands of invertebrates, including corals, sponges, shrimp, crabs, and lobsters. A complete list of marine species found in the Florida Keys National Marine Sanctuary can be viewed at http://floridakeys.noaa.gov/scipublications/speciesList.pdf (Levy *et al.,* 1996). This diversity contributes to the designation of Florida as the "fishing capital of the world" by the state legislature (FWC, 2003). The coastal marine ecosystem of the FK/DT supports a vital fisheries and a tourism-based economy that generated an estimated 71,000 jobs and U.S. $6 billion of economic activity in 2001 (Johns *et al.,* 2001).

Fisheries in South Florida are complex. Adult reef fish are caught for food or sport around bridges and on offshore patch and barrier reefs. Commercial and sport fisheries also target Caribbean spiny lobster (*Panulirus argus*), marine aquarium fishes, and invertebrates, both inshore and offshore. The discussion here focuses on a relatively few taxa chosen to represent different roles played by fish and shellfish in the FK/DT ecosystem. The **snapper-grouper complex** is a group of reef-based fish species, comprised of 18 species of groupers, 13 species of snappers, 13 species of grunts, hogfish, and great barracuda (Ault *et al.,* 1998), that are important to the recreational fishery. The **Caribbean spiny lobster** is found throughout the Caribbean and the western Atlantic from Rio de Janeiro, Brazil, in the south to North Carolina, USA, in the north. The **long-spined sea urchin** (*Diadema antillarum*) occurs throughout the western Atlantic and Caribbean. Although not fished, the herbivorous long-spined sea urchin plays an important role in maintaining the health of coral reefs throughout the Caribbean.

Species in the **snapper-grouper complex** utilize a mosaic of cross-shelf habitats and oceanographic features over their life spans (Ault and Luo, 1998, Ault *et al.,* 2005a; Lindeman *et al.,* 2000). Most adults spawn on the barrier reefs and sometimes form large spawning aggregations (Domeier and Colin, 1997). The Dry Tortugas region, in particular, contains numerous known spawning aggregation sites (Schmidt *et al.,* 1999). Pelagic eggs and developing larvae are transported from spawning sites along the barrier reef tract by a combination of seasonal wind-driven currents and unique animal behaviors to eventually settle as early juveniles in a variety of inshore benthic habitats (Lee *et al.,* 1994; Ault *et al.,* 1999b, 2002). Some of the most important nursery habitats are located in the coastal bays and near barrier islands (Lindeman *et al.,* 2000; Ault *et al.,* 2001, 2002). As individuals develop from juveniles to adults, habitat utilization patterns generally shift from coastal bays to offshore reef environments.

Reef fishery that targets the snapper-grouper complex has been intensively exploited over the past 75 years, during which the local human population has grown exponentially and generated concerns over sustainable fishery productivity. Many reef species are extremely sensitive to exploitation (Coleman *et al.,* 2000; Musick *et al.,* 2000; Ault *et al.,* 2008), and coastal development subjects coral reefs to a suite of other stressors that can cumulatively impact reef fish populations by degrading water quality and damaging nursery and adult habitats (Bohnsack and Ault, 1996; Lindeman *et al.,* 2000; Jackson *et al.,* 2001; Porter and Porter, 2001).

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. The coastal marine ecosystem of the FK/DT 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 coral reef fauna of South Florida are remarkably similar to that of the Bahamas and Cuba. The lack of land barriers, connectivity of water masses, and ocean currents facilitate larval transport of progeny among these areas. 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. Here they seek out 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.

In Florida, the **long-spined sea urchin** is found in almost all marine habitats, including rock, coral reefs, mangroves, seagrass beds, and sandy flats, in shallow coastal waters from Pensacola through the Florida Keys to Cape Canaveral (Ogden and Carpenter, 1987). A herbivore, adult animals shelter in crevasses and forage at night, often returning to the same crevasse. On Caribbean coral reefs, the long-spined sea urchin feeds preferentially on attached algae. When a healthy population of urchins is present, their grazing is believed to effectively control the biomass of macroalgae on the reefs. This promotes development of the high proportion of cover by live stony corals that indicates a healthy reef ecosystem. The demise of the long-spined sea urchin throughout the Caribbean in the 1980s and again in the Florida Keys in the 1990s corresponded with periods of general decline in the coral reef ecosystems in this region.

Attributes People Care About

People care about sustaining the multispecies coral reef fisheries in the Florida Keys. This is a key conservation concern, given their economic and ecologic importance, the significant dependence of subsistence and artisanal fishers on reef fisheries for their livelihoods, and the considerable and growing threats to coral reef habitats (i.e., coral bleaching and disease, pollution, and climate change). People care about maintaining large expanses of healthy coral in the ecosystem. Overgrowth of the reef by benthic algae signals degraded conditions in the ecosystem, and this is considered undesirable. The presence of herbivorous fish and, especially, the long-spined sea urchin on the reef are important to controlling the growth of algae and promoting a high proportion of cover by live coral.

Attributes We Can Measure

Diverse uses of the FK/DT fisheries requires equally diverse sources of quantitative information to track the condition of the faunal populations that support these uses. The National Marine Fisheries Service and the Florida Fish and Wildlife Commission conduct regular monitoring and assessment of information, such as landings, fishing effort, and biostatistical data, collected in connection with the commercial fisheries. However, other uses of the fisheries in the Keys, which include the bait fishery, the for-hire guide and charter fishery, the aquarium fishery, the sport fishery, spearfishing, diving, and the non-extractive uses of diving and snorkeling for wildlife viewing are equally important economically. In recognition of the need to track the condition and sustainability of fish populations through critical spatial data not included in the fisheries-dependent monitoring and assessment, there is also an ongoing fisheries independent monitoring program in the Florida Keys.

The multiagency fisheries independent monitoring program gathers information that can be used to assess the sustainability of both exploited and non-exploited populations, including those that make up the snapper-grouper complex (Brandt *et al.,* 2009; Smith *et al.,* 2011a, 2011b). Sustainability refers to the ability of an exploited stock to produce goods and services, including yields at suitable levels in the short term, while maintaining sufficient stock reproductive capacity to continue providing these goods and services into the indefinite future (Walters and Martell, 2004). The attributes measured by the fisheries independent monitoring (Table 1) relate directly to parameters in theoretically-based population models that combine the effects of ecosystem dynamics and human impacts via mortality from fishing (Ault *et al.,* 1998, 1999b, 2003, 2005a; Wang *et al.,* 2003). These models explicitly represent the population processes of recruitment, growth, reproduction, mortality from natural causes, and mortality from fishing. The measured attributes provide a metric of abundance, or biomass, and its distribution by age within the population of each species. Relationships in the models allow one to infer from these data the level of fishing mortality for each species and, most importantly, assess whether each population is sustainable under current levels of fishing.

The impact of fishing on populations is normally evaluated as a tradeoff between yield (in biomass) extracted by the fishery relative to the biomass of spawners remaining in the sea that are required to ensure sustained production. This concept is illustrated using two widely used fishery management benchmarks: yield-per-recruit (YPR) and spawning potential ratio (SPR). YPR is the expected lifetime yield of a cohort scaled to annual recruitment of newborns for a given combination of fishing mortality rate and minimum capture age or size. SPR is the expected lifetime spawning biomass of a cohort for a given combination of fishing mortality and age of capture scaled to the unexploited lifetime spawning biomass. In the U.S. South Atlantic, the federal minimum standard is 40 percent SPR for goliath grouper (*Epinephelus itajara*) and 30 percent SPR for other reef fish stocks (U.S. Department of Commerce, 2002). These benchmark values are derived from density-dependent, stock-recruitment theory where the number of recruits to a population is expected to be approximately the same at or above the minimum SPR threshold. The maximum YPR value at which SPR is at or above the 30 percent threshold denotes the level of exploitation expected to produce "maximum sustainable yield" (MSY).

Table 1: Atrributes measured in fisheries-independent and fisheries-dependent monitoring.

- **Population statistics**
  - Size-structured abundance
  - Spawning stock biomass
  - Coral reef habitat quality and distribution
- **Catch/yield**
  - Catch rates
  - Yields
- **Species diversity**
  - Species composition (richness)
  - Habitat occupancy

Sustainability analyses based on fisheries independent monitoring involve comparison of various population metrics at current levels of fishing mortality against standard fishery management sustainability benchmarks. Typically, numerical simulation models are configured to assess several reference points to address several stock sustainability risks, including fishery yields, spawning potential ratio (SPR; Clark, 1991), and precautionary control rules (Restrepo and Powers, 1999). Estimated SPRs are compared to U.S. federal standards which define 30 percent SPR as the threshold below which a stock is no longer sustainable at current exploitation levels (Gabriel *et al.*, 1989; Restrepo *et al.*, 1998). Evaluation of control rules involves determination of Fmsy (F–fishing mortality rate generating maximum sustainable yield, MSY) and Bmsy (population biomass at MSY) typically defined as F = M (natural mortality rate) as a proxy for Fmsy (Quinn and Deriso, 1999; Restrepo and Powers, 1999).

Drivers of Change

Fish and shellfish in the FK/DT coastal marine ecosystem are threatened by (1) fishing, (2) disease, (3) non-native species, (4) alterations to benthic habitats (e.g., loss of mangroves and seagrasses to shoreline development, channel dredging, and ship groundings), and (5) alterations to water quality (e.g., pollution, nutrification, and turbidity), quantity, and timing of freshwater inflows (Figure 1). The effects of fishing include the direct effect of increased mortality, as well as the removal of key prey (e.g., shrimp, baitfish) and predators (e.g., barracuda, sharks). Other environmental issues facing the FK/DT include coral declines from diseases and bleaching, invasion of exotic species, shifts to algal dominance, and damage from contact by anchors, grounded vessels, divers, snorkelers, and fishing gear. In addition, hurricanes have a 16 percent annual probability of striking the Florida Keys (Neumann, 1987) and damaging habitat. Looking at the full spectrum of impacts suggests that achieving sustainable reef fisheries will likely entail substantially more analysis of inter-related factors than simply assessing fishing mortality rates for a few snapper and grouper species (Bohnsack and Ault, 1996; Ault *et al.,*1999b; Lindeman *et al.,* 2000).

Fishing

Snapper-Grouper Complex

Intensive exploitation and overfishing is perhaps the major threat to these fisheries of the Florida Keys ecosystems (Russ, 1991; Haedrich and Barnes, 1997; Ault *et al.,* 1998, 2005a, 2008). 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 sizes. Third, gear and fishery impacts with critical habitats can reduce the quality and productivity of the environment that supports these valuable fisheries. In coastal bays and near barrier islands, juvenile pink shrimp are commercially targeted as live bait for the recreational fishery. Both food and sport fisheries target pre-spawning subadult pink shrimp as they emigrate from coastal bay nursery grounds to offshore spawning grounds (Ault *et al.,* 1999a).

Inshore, sport fisheries pursue highly prized game fishes, including tarpon, bonefish, spotted seatrout, permit, sheepshead, black and red drum, and snook, while commercial fisheries primarily target sponges and crabs. Offshore of the deep margin of the barrier reef, commercial and sport fisheries capture an assortment of species including amberjack, king and Spanish mackerel, barracuda, sharks, and small bait fishes (e.g., *Exocoetidae, Mullidae, Carangidae, Clupeidae, and Engraulidae*). Farther offshore (seaward of the 40 m isobath), commercial and sport fisheries catch dolphinfish, tunas, and swordfish, and sport fishers target sailfish, wahoo, and white and blue marlin.

Caribbean Spiny Lobster

The Caribbean spiny lobster is perhaps the most important commercial fishery species in the Florida Keys, but it is also intensively fished by the recreational sector. The commercial fishery for Caribbean spiny lobster in the southeast United States began in Florida in the late 1800s as an artisanal and bait fishery for finfish. Transition to a food fishery occurred when construction of the railroad from Miami to Key West and, later, the Overseas Highway, improved transportation links to the mainland. The current heavy exploitation 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 (Ehrhardt *et al.,* 2009).

In the Florida Keys, damage to benthic habitats from fishing gear impacts and marine debris represent important indirect pressures on the fisheries. For example, regular yet unintended trap loss in the lobster and stone crab trap fisheries results in trap ropes wrapping around coral

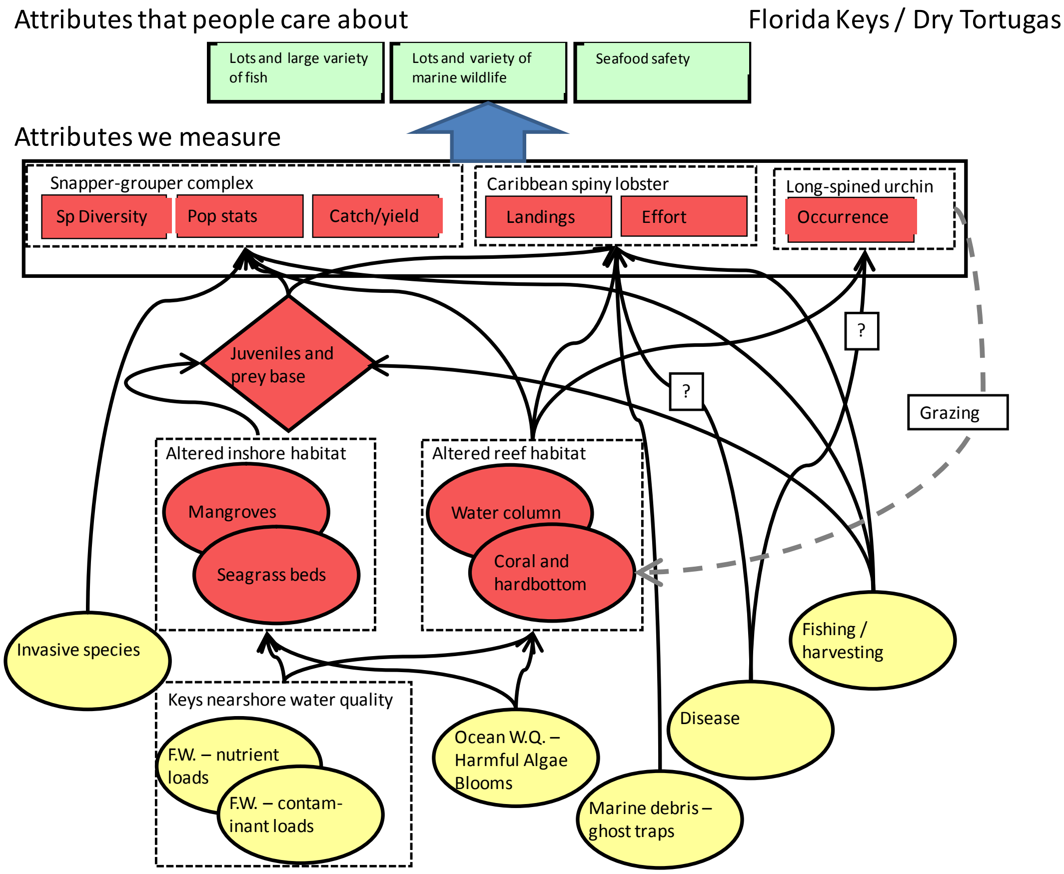

Figure 1. Fish and shellfish submodel diagram for the Florida Keys/Dry Tortugas.

heads and abrading or killing coral colonies. Combined, the two fisheries utilize approximately 815,000 traps per season in addition to an unknown number of recreational stone crab traps (five per person allowable with a Florida saltwater fishing license) that have the same potential for habitat impact. In addition, lobster or stone crab traps can continue "fishing" even after they have been lost, which leads to continued mortality of marine organisms that are too large to escape the traps after capture.

Long-Spined Sea Urchin

There is no fishing of the long-spined sea urchin in the Florida Keys.

Disease

Disease exerts a significant influence on faunal populations in the Caribbean region. Perhaps the best known of this fact is the viral epidemic that struck the long-spined sea urchin between 1983 and 1984. 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 taken hold in the Caribbean 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).

Non-Native Species

The non-native lionfish threatens the ecosystem by altering the structure of native reef fish communities by out-competing native reef organisms and reducing forage fish biomass (Morris and Whitfield, 2009). Venomous protective spines, combined with their aggressive feeding habits, unique reproduction, and lack of predators contribute to their competitive advantage. Impacts from lionfish include direct competition with groupers for food and predation of reef fish and crustaceans (Ruiz-Carus *et al.,* 2006; Albins and Hixon, 2008; Morris and Atkins, 2009). Observations of sharp increases in lionfish abundance since 2009 throughout the FK/DT also poses a danger to divers and fishermen from their venomous spines and a potential disruption of the ecological balance of the ecosystem (Ruttenberg *et al.,* 2012).

Habitat Degradation

Habitat degradation resulting from other human activities include coastal development, altered freshwater flow, and changes in water quality from pollution, sedimentation, and excess nutrients (CERP, 1999; Cowie-Haskell and Delaney, 2003). Damages related to fishing gear and general boat use also contribute to habitat degradation. Human impacts have grown as a result of Florida's tenfold population growth from 1.5 million people in 1930 to 16 million in 2000. In 2000, over five million residents, nearly a third of Florida's population, lived in the five southern counties adjacent to coral reefs (Palm Beach, Broward, Miami-Dade, Monroe, and Collier). In addition, over three million tourists visit the Florida Keys annually (Leeworthy and Vanasse, 1999).

Pressures

Fishing

Precise data on trends in coral reef fishing effort, combining both commercial and recreational activities, do not exist, but these trends are reflected by 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 1964-2002, the number of registered recreational boats in South 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.

The increased fishing fleet size has been accompanied by a number of technological advances that have been estimated to have quadrupled average fishing power (Mace, 1997), i.e., the proportion of stock removed per unit of fishing effort (Gulland, 1983). These advances include improvements in fishing tackle, hydroacoustics (depth sounders and fish finders), navigation (charts and global positioning systems), communication, and inexpensive, efficient, and more reliable vessel and propulsion unit designs (Bohnsack and Ault, 1996; Ault *et al.,* 1997, 1998). These fishing trends have thus become an obvious concern to the fishery sustainability and persistence of the coral reef ecosystem.

Although fishing pressure (i.e., number of trips, traps, angler days, etc.) from both the commercial and recreational fisheries declined from 1995 to 2008, it is uncertain if these trends will continue. For example, information from socio-economic surveys in 1995-1996 showed over 572,000 visitors and residents participated in over 2.8 million days of recreational fishing in the Florida Keys (Leeworthy and Wiley, 1996; Leeworthy, 1996; Leeworthy and Wiley, 1997). Similar surveys in 2007 and 2008 showed almost 416,000 visitors and residents participated in almost 2.1 million days of fishing in the Florida Keys and Key West (Leeworthy *et al.,* 2010; Leeworthy and Morris, 2010). This represents a 25 percent decline in recreational fishing effort over the 12-year period. However, this decrease in pressure has an offsetting trend in that the growth in average fishing power (the proportion of stock removed per unit of fishing effort) may have quadrupled in recent decades. The increase results from technological advances in fishing tackle, hydroacoustics (depth finders and fish finders), navigation (charts and global positioning systems), communications, and vessel propulsion (Bohnsack and Ault, 1996; Mace, 1997). Because of this, there remains a significant but largely undocumented effect of tens of thousands of recreational fishers who target hundreds of species using mostly hook-and-line and spear guns (Bohnsack *et al.,* 1994a).

For the 1996 to 2006 period, Murray and Associates, Inc. (2007) summarized various measures of fishing effort for Monroe County relative to "other Florida counties" (Table 2). Over this period, all measures of fishing effort declined more rapidly in Monroe County relative to all other counties in Florida, except for stone crab permits. Trends in recreational and commercial fishing pressure in Monroe County/Florida Keys are in decline due to a number of fishery and extra-fishery factors, including stagnant ex-vessel values (the revenue the fisherman receives for his catch) resulting from low demand, higher landside prices such as cost of living, gear, crew, etc., and less waterfront space availability (Leeworthy and Wiley, 1996; Leeworthy, 1996; Sharp *et al.,* 2005; Leeworthy *et al.,* 2010; Leeworthy and Morris, 2010).

Non-Native Species

Red lionfish, formerly residents of the western Pacific Ocean, Red Sea, and eastern Indian Ocean, were first reported in the 1980s along South Florida and are now well established along the southeast U.S. and Caribbean (Ruiz-Carus *et al.,* 2006; Morris *et al.,* 2009). Reports of lionfish in the sanctuary 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, sighting 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 (C. McHan, FWC, personal observation; M. Butler, Old Dominion University, personal communication; Ruttenberg *et al.,* 2012), suggesting a pervasive invasion is occurring across all the habitats of the Florida Keys ecosystem. The increasing abundance and wider distribution of lionfish in the South Atlantic Bight, Bermuda, Florida, and the Bahamas indicates that lionfish are perhaps the first marine fish species to successfully establish a breeding population in the tropical central western Atlantic.

Status and Trends

Snapper-Grouper Complex

Ault *et al.* (1998, 2005b) assessed the status of reef fish stocks and determined that 13 of 16 groupers, seven of 13 snappers, one wrasse (hogfish), and two of five grunts were overfished according to federal (NOAA's National Marine Fisheries Service) standards. In addition, some stocks appeared to have been chronically overfished since the 1970s, with the largest, most desirable species depleted first, followed by increasingly smaller and less desirable species with time (Ault *et al.,* 1998). The average size of adult black grouper in the upper Keys was about 40 percent of its 1940 value, and the spawning stock for this species was less than 5 percent of its historical, unfished maximum potential (Ault *et al.,* 2001). In subsequent analyses, Ault *et al.* (2005a, 2005b, 2009) determined that 25 of the 34 species within the snapper-grouper complex for which sufficient data were available were experiencing overfishing.

Table 2. Southeast regional stocks that are subject to overfishing or are overfished as defined by NOAA's National Marine Fisheries Service. The list includes species in both the South Atlantic and Gulf of Mexico fishery management council jurisdictions (Source: NMFS, 2010).

Subject to Overfishing	Overfished
Vermillion snapper (South Atlantic only)	Red snapper
Red snapper	Snowy grouper (South Atlantic only)
Snowy grouper (South Atlantic only)	Black sea bass (South Atlantic only)
Red grouper (South Atlantic only)	Red porgy (South Atlantic only)
Black sea bass (South Atlantic only)	Pink shrimp (South Atlantic only)
Gag grouper	Red grouper (South Atlantic only)
Speckled hind (South Atlantic only)	Gag grouper (Gulf of Mexico only)
Warsaw grouper (South Atlantic only)	Gray triggerfish (Gulf of Mexico only)
Tilefish (South Atlantic only)	Greater amberjack (Gulf of Mexico only)
Greater amberjack (Gulf of Mexico only)	
Gray triggerfish (Gulf of Mexico only)	

Generally, there is a very high exploitation rate in the Florida Keys from both recreational and commercial fishing efforts. Trends in reef fish landings from 1981 to 1992 were reported for the Florida Keys by Bohnsack *et al.* (1994a). Depending on the year, recreational landings comprised between 40 percent and 66 percent of total landings. Reef fishes accounted for 58 percent of total fish landings. In its 2010 report to Congress, NOAA's National Marine Fisheries Service classified nine species that are landed in the Florida Keys as overfished (i.e., depleted below minimum standards), and 11 species as subject to overfishing (i.e., being fished at a rate that would lead to being overfished), with some overlap between the two categories (NMFS, 2010; Table 2).

Caribbean Spiny Lobster

Invertebrates (Caribbean spiny lobster, shrimp, and stone crabs) comprise 63 percent of total landings. Commercial fishing catch declined from 21.8 million pounds in 1995-1996 to 9.6 million pounds in 2008, a 56 percent decrease. Fishing trips also declined 56 percent over this period, from 67,422 trips in 1995-1996 to 29,681 trips in 2008. This was a greater decline than what occurred across the entire state of Florida. Florida's total catch declined about 34 percent during the same period, while trips declined about 47 percent. This decline was due in part to changes in fishery management designed to reduce overall fishing effort, as well as decreasing demand for Caribbean spiny lobsters, which is the dominant fishery in the Florida Keys. The FK/DT region historically accounted for 89 percent of commercial Caribbean spiny lobster catch (FWRI, 2010).

Long-Spined Sea Urchin

Historical surveys of the long-spined sea urchin prior to the 1983 and 1984 Caribbean-wide mass mortality event are limited for the Florida Keys. Surveys carried out in the early 1990s suggested that the population was recovering slowly, with densities on shallow spur and groove reefs approaching one tenth (i.e., 0.5-0.6 individuals per 10 square feet) of their pre-1983 level (Forcucci, 1994). Over an 11-year period (1999-2010), researchers examined densities and test sizes of the long-spined sea urchin and other sea urchins at more that 1,100 Florida Keys sites spanning 217 miles (350 kilometers) and encompassing multiple habitat types from inshore to the deeper fore-reef slope. Surveys since 1999 indicate that current densities are still well below one individual per square meter.

Discussion

Consequences of Overfishing

The resulting severe reduction in numbers of large fishes and loss of spawning aggregations deleteriously affects ecosystem integrity and biodiversity. Former spawning aggregation sites in the FK/DT ecosystem are not functioning the way they did historically. Quantitative anecdotes from experienced fishers point towards sharply reduced numbers of spawning aggregations and fewer, much smaller individuals within those that are still present. Researchers from NOAA's National Marine Fisheries Service and Florida's Fish and Wildlife Research Institute have been monitoring one recovering spawning aggregation site for mutton snapper (*Lutjanus analis*) at Riley's Hump in the Tortugas South Ecological Reserve since 2004 (Burton *et al.,* 2005; Feeley *et al.,* 2012). According to diving observers, in 2009-2011 "thousands" of mutton snapper aggregated for spawning at Riley's Hump (Feeley *et al.,* 2012).

Although the no-take marine reserves (NTMR) within the sanctuary were not designed as a fishery management tool *per se*, results from a FWC five-year monitoring project concluded that Sanctuary Preservation Areas were too small to protect Caribbean spiny lobsters from the fishery, but the larger Western Sambo Ecological Reserve (WSER) did function to some degree as a fishery reserve (Cox and Hunt, 2005). There, the mean size of legal lobsters and the frequency of encounters in large lobsters in areas adjacent to the WSER suggested that lobsters were likely emigrating from the WSER to fished areas, thus this zone may have served to enhance fishery landings to some extent. The WSER does not encompass all of the habitats utilized by adult Caribbean spiny lobsters during their life history, and inclusion of the adjacent outlier reef would serve to protect lobsters from fishery exploitation (Cox and Hunt, 2005). On the other hand, a series of synoptic fishery-independent reef fish visual census research cruises spanning two years before and 10 years after NTMR implementation strongly indicated that these NTMRs, in conjunction with traditional fishery management control strategies, were helping to build sustainable fisheries while protecting the fundamental ecological dynamics of the FK/DT coral-reef ecosystem (Ault *et al.,* 2006, 2013).

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Benthic Habitat: Coral and Hardbottom

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In a nutshell

- Coral reefs and hardbottom communities are unique ecosystems that support a diverse community of fish and invertebrate species.
- The recreational and commercial fishing and harvesting activities centered around coral reefs provide a multi-billion dollar income to the local economy.
- Coral reefs in Florida and around the world have undergone a dramatic decline in the recent past caused by human (e.g., overfishing, eutrophication, pollution) and natural (e.g., storms, extreme temperatures, diseases) disturbances.
- The protection of reef resources is crucial to southeast Florida where a substantial portion of revenue and jobs are dependent both directly and indirectly on the status of reef resources.

The reef communities of the Florida Reef Tract represent the only living tropical coral reef system in the continental U.S. (Figure 1). Reefs of the Florida Keys, from Key West to Key Biscayne, are commonly divided into two main types: offshore shelf-margin bank reefs and lagoonal patch reefs. Offshore bank reefs with spur and groove habitats are generally oriented perpendicular to the shelf and are found on the seaward face of the shelf margin (Marszalek *et al.,* 1977). Patch reefs are high-relief features (up to 9 m of vertical relief) located within the inner lagoon between the Florida Keys and the shelf-margin reefs. Patch reefs are commonly dome- or linear-shaped and range in diameter from a few meters to up to 700 m (Marszalek *et al.,* 1977; Jaap, 1984). Several interacting factors have contributed to the consideration of this ecologically, economically, and aesthetically unique system as an "ecosystem at risk" (Bryant *et al.,* 1998). Over 40 species of stony corals have been documented on Florida reefs. Other dominant taxa include octocorals, sponges, and zoanthids. Historically, the shallow areas of shelf-margin reefs were dominated by the fast-growing branching genus *Acropora* (*A. palmata* and *A. cervicornis*), but these species have undergone a drastic decline and are now listed as threatened under the U.S. Endangered Species Act (Porter and Meier, 1992; Miller *et al.,* 2002; NMFS, 2006). Dominant coral taxa on offshore reefs include *Porites, Montastraea, Diploria, Dicocoenia,* and *Siderastrea*. Patch reefs are dominated by medium-to-large colonies of boulder corals like *Montastraea, Diploria, and Siderastrea* (Lirman and Fong, 2007).

Low-relief hardbottom communities are another key component of the coastal habitats of South Florida. Hardbottom habitats in the Florida Keys can be found adjacent to the mainland and islands at depths from <1 m to >20 m. Hardbottom communities are characterized by a limestone platform covered by a thin layer of sediment and consist of a sparse mixture of stony corals, soft corals, macroalgae, and sponges (Bertelsen *et al.,* 2009). Many 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 (Blair and Flynn, 1989; Chiappone and Sullivan, 1994; Lirman *et al.,* 2003).

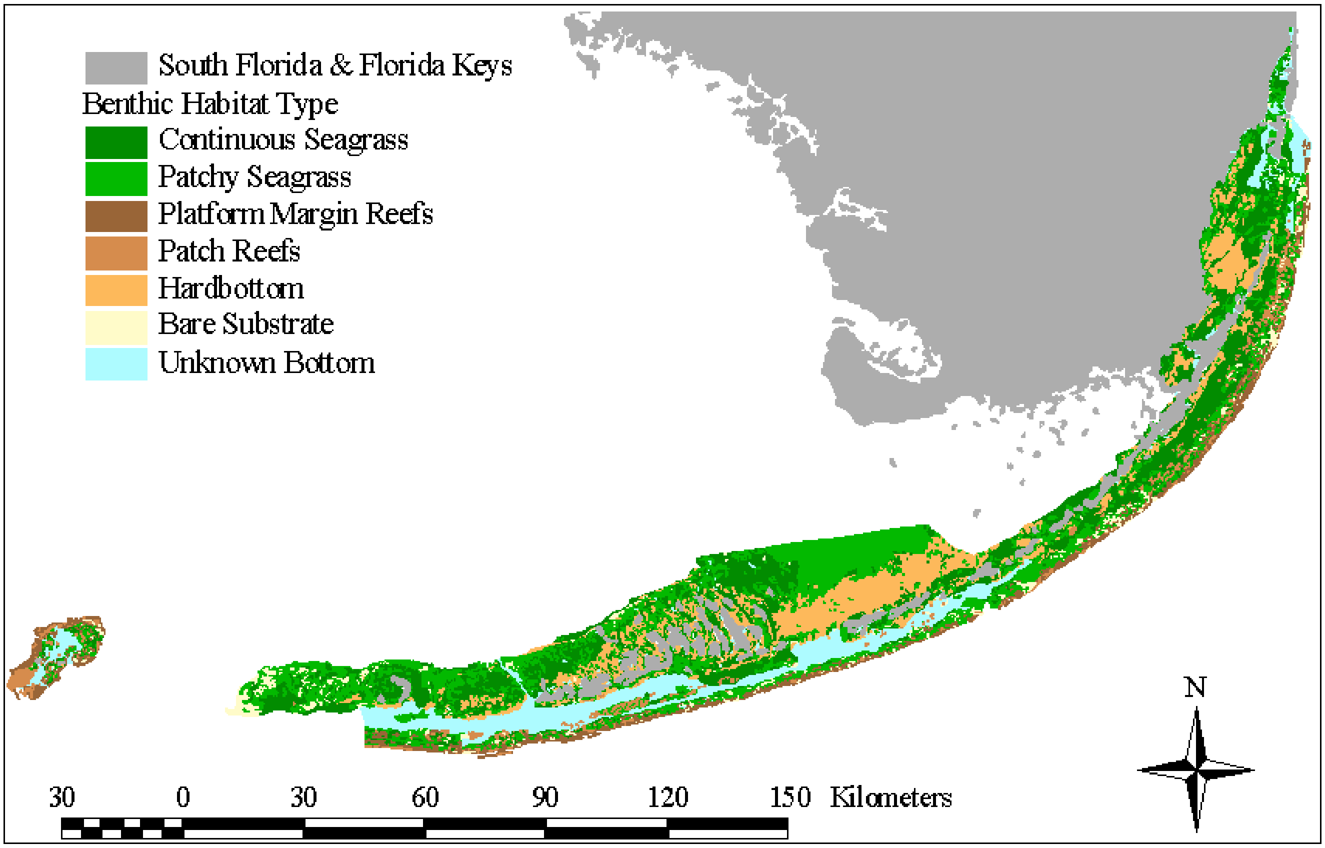

Figure 1. Benthic habitats of the Florida Keys (from Fourqurean *et al.,* http://serc.fiu.edu/seagrass/NearshoreWeb).

Role in the Ecosystem

Healthy reefs are vital to the economy of South Florida. A substantial portion of revenue and jobs in Florida are dependent both directly and indirectly on the status of their reef resources. In addition to the intrinsic value of coral reefs as centers of biodiversity and productivity, these habitats provide important services such as shoreline protection, sand production, building materials, nutrient cycling, carbon sequestration, adult and nursery habitat for fish and invertebrate species, fisheries resources, pharmaceutical and biomedical products, as well as societal services such tourism revenues, education and recreation opportunities, and cultural resources (Conservation International, 2008). Hardbottom communities can be important nursery habitats for shrimp and lobsters (Diaz, 2001; Butler *et al.,* 1995; Hunt, 2001; Bertelsen *et al.,* 2009) and have supported, in the past, commercial sponge fisheries (Cropper *et al.,* 2001).

The importance of coral reef habitats to the economic welfare of southeast Florida was evidenced in a study by Johns *et al.* (2001), which reported that reef-related expenditures generated more than $4 billion in sales and supported over 72,000 full- and part-time jobs in 2000-2001 in Monroe, Miami-Dade, Broward, and Palm Beach counties. On a worldwide basis, recent reports have estimated that the total net benefit of the world's coral reef ecosystems is nearly $30 billion/year (Cesar *et al.,* 2003). Moreover, the average global value of coral reef recreation has been estimated at $184 per visit (Brander *et al.,* 2007). Within the long list of services provided by these habitats, the following have been identified as the most valuable (Conservation International, 2008; Cesar *et al.,* 2003): (1) tourism and recreation (accounting for $9.6 billion of the total $29.8 billion global net benefit of coral reefs); (2) fisheries ($5.7 billion); (3) coastal protection ($9 billion); (4) biodiversity ($5.5 billion); and, more recently, (5) carbon sequestration (contribution to global economy not quantified yet).

Coral Reef Protection in South Florida

The current level of protection of reef resources varies among the counties of southeast Florida and ranges from unrestricted access to no-take and research-only areas with access limited by permitting. In 1990, the Florida Keys National Marine Sanctuary and Protection Act designated 9,950 km^2 of coastal waters in the Florida Keys as a Marine Protected Area to offer protection to over 1,400 km^2 of coral reef habitats found within the Sanctuary (http://floridakeys.noaa.gov) (Figure 2). In 1997, the management plan of the Florida Keys National Marine Sanctuary (FKNMS) created a network of protected zones to achieve biodiversity conservation, wildlife protection, and the separation of incompatible uses. Zone types include: wildlife management areas to minimize disturbance to sensitive wildlife and habitats; ecological reserves to protect large and contiguous habitats; sanctuary preservation areas (SPAs) to protect heavily used reefs; and special-use areas for scientific research, education, restoration, or monitoring.

The original 23 fully protected zones, where extractive and consumptive activities are prohibited, include 65 percent of the shallow coral reef habitats and 10 percent of all reef resources in the FKNMS (Keller and Donahue, 2006). In addition to the SPAs established in 1997, the Tortugas Ecological Reserve was implemented in 2001, increasing the amount of coral reef habitat within no-take zones to 10 percent within the Sanctuary. The Tortugas Ecological Reserve, located in the westernmost portion of the Florida Reef Tract, is the largest (517.9 km^2) of the Sanctuary's fully-protected zones. This reserve is located adjoining to the Dry Tortugas National Park (262 km^2) and its newly designated Research Natural Area (RNA; 129 km^2) where anchoring and fishing activities are not allowed. Together, the Tortugas Ecological Reserve and the Dry Tortugas National Park's RNA fully protect nearshore to deep reef habitats and form the largest marine reserve in the continental U.S.

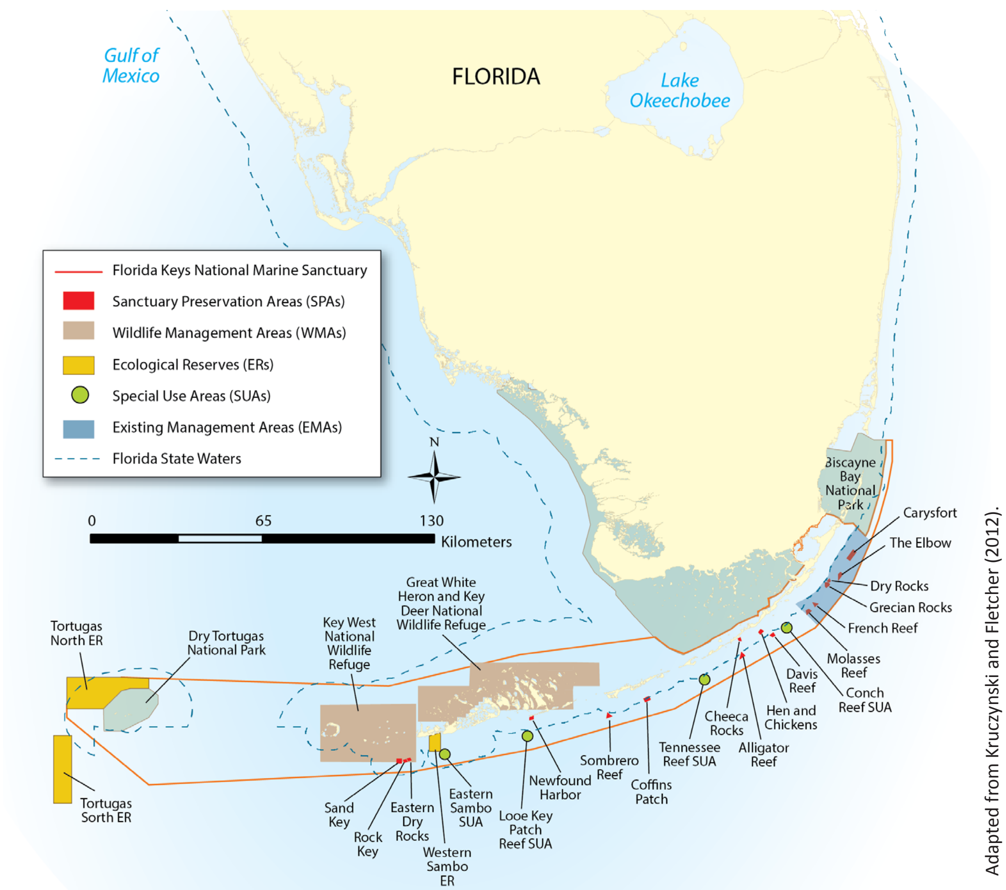

Figure 2. Map of the southeast Florida and the location of Biscayne National Park, Dry Tortugas National Park, and the Florida Keys National Marine Sanctuary.

Just north of the FKNMS boundaries, Biscayne National Park encompasses a large portion of the northern Florida Reef Tract with 291 km^2 of coral reefs and coral-dominated habitats. While extractive activities (e.g., fishing, spearfishing, lobster, and crab collection) are still permitted within Biscayne National Park, a revision of its General Management Plan is underway. Several of the alternatives proposed in this revision include the designation of management zones where fisheries resources and nursery habitats would be protected from fishing and other disturbances (http://www.nps.gov/bisc/parkmgmt/planning.htm). At present, the coral reef resources in the region north of Biscayne National Park (Miami-Dade to Martin counties) do not fall within any marine protected area.

In addition to areas with federal protection, reef resources are also found within a number of state parks and aquatic preserves that presently offer limited protection to corals and reef-associated resources. Examples of these include the Key West National Wildlife Refuge and Great White Heron National Wildlife Refuge, John Pennekamp Coral Reef State Park, Lignumvitae Key Botanical State Park, Biscayne Bay Aquatic Preserve, and the St. Lucie Inlet Preserve State Park. Lastly, the Oculina Bank Habitat Area of Particular Concern (HAPC), established in 1984, runs from Ft. Pierce to Cape Canaveral and protects deep-water populations of the ivory coral (Oculina).

Attributes People Care About

Coral reefs and hardbottom communities of the Florida Keys support attributes of the marine environment that people care about. These attributes are directly related to ecosystem services provided by the Florida Keys marine ecosystem:

- Abundance of healthy coral
- Abundance and large variety of fish and shellfish
- Ecosystem resilience to disturbance
- Protection from erosion and storms
- Critical habitat for protected species
- Aesthetics and recreation

Abundance of Healthy Coral

The essential characteristic of healthy coral reef habitats is the high abundance and diversity of stony and soft corals. Coral reefs are centers of biodiversity and productivity, and the services provided by these ecosystems are directly tied to their biodiversity. A wide range of coral morphologies provides a variety of niches for fish and invertebrates, and coral abundance is directly related to fish biomass. Moreover, the high topography, variety of sub-habitats, and diversity of species are the attributes that attract tourists, snorkelers, and divers to these ecosystems in Florida and elsewhere.

Abundance and Large Variety of Fish and Shellfish

Fish and macroinvertebrates are important ecological components of reef ecosystems and also sustain a productive commercial and recreational fisheries industry worldwide. In addition to their economic value, abundant and diverse fish and invertebrate stocks are an essential component of the "reef experience," and snorkelers and divers enjoy viewing these organisms as much as corals. Finally, a healthy fish and invertebrate trophic structure is essential for the growth and persistence of corals. Fish and invertebrate grazers play a major role in keeping the reef free of macroalgae that can outcompete and kill corals. Fish also play a major role in the recycling of nutrients within reefs.

Ecosystem Resilience to Disturbance

Periodic disturbances are an integral component of coral reef ecology, and coral reefs, like all other natural ecosystems, are in a constant state of damage and recovery. However, under healthy conditions, coral reef organisms are able to withstand and recover from disturbances. This ability to recover quickly from disturbance is an attribute that is highly valued by scientists, managers, and the public (Nyström and Folke, 2001). When disturbance thresholds are exceeded or multiple stressors compromise the recovery capabilities of reef organisms, coral reefs can enter into an alternate state of degradation from which it is increasingly more difficult to recover. Some of the attributes that make a reef community resilient to disturbance include an intact trophic structure, a high diversity of organisms, and good water quality.

Protection from Erosion and Storms

Corals are ecosystem engineers that can create large and complex three-dimensional carbonate structures that provide significant buffering from waves and currents. The presence of healthy, growing reefs provides valuable benefits in terms of storm and shoreline protection. This is especially important in Florida where a big part of the tourism economy is based on beach-related activities. Much like seagrasses that buffer water motion, coral reefs provide cost-effective, natural shore protection that reduces the need for costly beach renourishment and erosion control projects.

Critical Habitat for Protected Species

Florida reefs are essential habitat for the endangered green turtle and support threatened fisheries species like the Nassau grouper and queen conch. Florida reefs are also essential habitat for two species of threatened stony corals, staghorn (*A. cervicornis*) and elkhorn (*A. palmata*) corals.

Aesthetics and Recreation

Coral reefs, often described as the tropical rain forests of the ocean, provide a wonderful mosaic of diverse structures, colors, and even sounds! Healthy coral reefs with lots of fish and associated organisms provide a unique aesthetic experience that create long-lasting memories in those that have the opportunity to experience these magnificent ecosystems. Coral reefs also provide a number of recreational opportunities that are highly valued by visitors. These include fishing, collecting, diving, snorkeling, and glass-bottom viewing.

Attributes We Can Measure

A number of large-scale, long-term monitoring programs have been established in the Florida Keys in recent years to evaluate the status and trends of coral reef communities. These monitoring programs include the NOAA/National Undersea Research Center program (1999-present, http://people.uncw.edu/millers/CoralReef_QuickLooks.htm), the Coral Reef Monitoring Project (CREMP, 1994-present, http://ocean.floridamarine.org/fknms_wqpp/pages/cremp.html), and the more recent Florida Reef Resilience Program (FRRP, 2005-present, http://frrp.org).

In contrast, coordinated efforts to evaluate the status and trends of hardbottom communities are less common or have restricted spatial and temporal coverage. Baseline abundance and distribution of organisms within hardbottom habitats have been documented by Lirman *et al.* (2003), Fourqurean *et al.* (http://serc.fiu.edu/seagrass/NearshoreWeb), and Bertelsen *et al.* (2009). Hardbottom communities within the Florida Reef Tract are also being monitored as part of the National Undersea Research Center program (http://people.uncw.edu/millers/CoralReef_QuickLooks.htm) and the Florida Reef Resilience Program (http://frrp.org/).

The monitoring programs designed to determine regional-scale gradients in the status of coral reefs and hardbottom communities commonly collect information on the following attributes:

- Reef structure
- Diversity
- Species abundance
- Species distribution
- Size of coral colonies
- Partial mortality
- Disease and bleaching prevalence

Reef Structure

Structure and function are closely tied in coral reefs where reef-building stony corals provide the three-dimensional structure that is utilized as essential habitat for associated organisms. Thus, measures of topographical structure or relief are commonly collected in monitoring programs as a proxy for reef condition and habitat value. The close relationships between coral abundance, reef topographical structure, and habitat value for fisheries have been highlighted by recent studies of reef degradation that have shown that declines in coral abundance have resulted in a general "flattening" of reefs (Alvarez-Filip *et al.,* 2009) and a corresponding loss of fisheries resources (Paddack *et al.,* 2009) worldwide. Topographical structure is commonly measured using rugosity-chain measures or coral colony heights (McCormick, 1994; Kramer and Lang, 2003).

Diversity

Coral reefs are known centers of biodiversity, and diversity or species richness are commonly recorded in monitoring programs through cumulative species counts (Rutten *et al.,* 2009). While no recent records of species losses have been recorded in Florida reefs and hardbottom communities, loss of species from certain reefs or areas have been recorded during the recent patterns of reef decline (Porter *et al.,* 2002). Most monitoring programs focus on stony corals; others do collect richness information on soft corals, sponges, and associated macroinvertebrates (NOAA-NURC).

Species Abundance

The abundance of coral colonies is commonly documented as the proportion of the bottom occupied by a give taxon in a two-dimensional view. The abundance of coral taxa provides a good snapshot of the status of a given site and, through repeat surveys, changes in cover can provide information of temporal trends in coral reef or hardbottom status. Coral cover has always been synonymous with coral reef condition, and measurements of percent coral cover are made (either directly or indirectly) by most coral reef monitoring programs using point or line-intercept methods (AGRRA, NOAA-NURC, CREMP) or colony measurements (Lirman and Fong, 2007; FRRP) (Porter *et al.,* 2002; Miller *et al.,* 2002). In addition, the proportion of the bottom occupied by corals, monitoring programs also collect data on the abundance/cover of other key taxa like sponges, zoanthids, and macroalgae.

Species Distribution

Changes in the distribution of coral and associated taxa can often be indicative of changes in environmental conditions. Thus, the spatial distribution of benthic organisms is commonly documented in Florida using habitat-specific and spatially structured monitoring approaches (Miller *et al.,* 2002; Lirman and Fong, 2007; Bertelsen *et al.,* 2009). Spatially structured monitoring approaches maximize survey efficiency and also allow managers to delineate critical habitat for protected species like the genus *Acropora* (Smith *et al.,* 2011; http://www.nmfs.noaa.gov/pr/species/criticalhabitat.htm). Most species of corals have widespread distributions within reef and hardbottom habitats of the Florida Keys, but some species have been lost within specific plots and reefs during the recent declining trends (Porter *et al.,* 2002).

Size of Coral Colonies

Although changes in coral cover and diversity can provide good indicators of reef degradation (Porter *et al.,* 2002), these measures alone can't be used to examine sublethal effects of chronic exposure to stressors. Thus, most monitoring programs have incorporated demographic indicators (e.g., size of colonies, prevalence of fragmentation and fission, recruitment) to supplement measurements of coral cover to reveal more subtle differences among populations that cover and diversity measures alone may miss. Population size structure has been shown to provide good indicators of stress and condition (Bak and Meesters, 1999; Ginsburg *et al.,* 2001; Nugues and Roberts, 2003). All large-scale monitoring programs in the Florida Keys include colony size measurements within their protocols. The abundance of juvenile corals (<4 cm in diameter) is also used as an indicator of recruitment success (Lirman and Fong, 2007). Size measurements of sponges on other benthic organisms are also collected as part of monitoring programs on hardbottom habitats (Cropper *et al.,* 2001; Lirman *et al.,* 2003).

Partial Mortality

The amount of recently dead tissue on coral colonies is being used increasingly as an indicator of the impact of recent disturbances. Recent tissue mortality is described as portions of a coral colony devoid of living tissue where the corallite structure is still present and allows identification to the species level (Kramer and Lang, 2003). This indicator is intended to provide information on the impacts of disturbance with impacts concentrated within the recent past (weeks-months). Percent recent mortality is commonly estimated as the proportion of a coral colony that exhibits recent tissue mortality, and this metric is commonly averaged within and among sites for all colonies present and compared to similar measurements taken immediately after a major disturbance like a bleaching episode (Kramer, 2003; FRRP) or, more recently, a cold-water anomaly (Lirman *et al.,* 2011).

Disease and Bleaching Prevalence

One of the main sources of coral mortality in Florida and the Caribbean in the past decades has been coral diseases (Porter *et al.,* 2001; Richardson and Voss, 2005). In fact, the large-scale demise of *Acroporid* corals in the Florida Keys has been attributed to outbreaks of white-band disease (Precht and Miller, 2007; Patterson *et al.,* 2011). Similarly, warm-water anomalies that cause coral bleaching (i.e., the expulsion of the endosymbiotic zooxanthellae) have been a major source of mortality in Florida and elsewhere (Jaap, 1979, 1985; Baker *et al.,* 2008). All large-scale monitoring programs in place in the Florida Keys include measurements of bleaching and disease prevalence, commonly estimated as the percentage of colonies exhibiting signs of disease or bleaching. In addition to prevalence, the proportion of the colony surface affected by these two types of disturbance can be estimated.

Drivers of Change

The human drivers identified as having a direct influence on the state of coral reefs and hardbottom communities include both near-field (i.e., acting within the region) and far-field (i.e., at global scale) (Figure 3). Near-field drivers include coastal construction, tourism and recreation, industry, agriculture, energy, transportation, waste disposal, recreational and commercial fisheries, and water management. Far-field drivers include global climate change and climatic extremes (e.g., sea-level rise, high and low temperatures, storms, acidification), diseases, and invasive species.

The potential causal factors implicated in the observed decline in coral reefs and hardbottom habitats in Florida are those common to other reef systems around the world (Brown, 1997) and include: hurricanes (Porter and Meier, 1992; Lirman and Fong, 1997); ship groundings (Lirman and Miller, 2003; Gilliam, 2006); the demise of the sea urchin *Diadema antillarum* and increased macroalgal competition (Forcucci, 1994; Lirman, 2001); coral diseases (Porter *et al.,* 2001; Richardson and Voss, 2005); increased nutrients (Lapointe *et al.,* 2002); sedimentation (Dustan, 1999); high temperature and bleaching events (Jaap, 1979, 1985; Manzello *et al.,* 2007); cold-water events (Hudson, 1981; Walker *et al.,* 1982; Lirman *et al.,* 2011); and phytoplankton (Hu *et al.,* 2003) and cyanobacterial (Butler *et al.,* 1995; Paul *et al.,* 2005) blooms.

Mechanisms of Change

Direct impacts to coral reefs and hardbottom communities can be generally grouped into lethal and sublethal impacts. While sublethal impacts (e.g., reduced growth, reduced calcification) may be precursors of lethal impacts if pressures exceed a certain threshold, recovery from sub-lethal impacts can also take place. Impacts can also be grouped into functional (e.g., reduced productivity) and structural (e.g., reduced topographical complexity, reduced diversity). Often, functional and structural impacts are tightly linked. For example, reduced growth can result in reduced topography which, in turn, can result in reduced primary productivity.

The impacts that are directly related to the ecological, economic, and societal services that coral reefs and hardbottom habitats provide include: mortality of key benthic components (hard and soft corals, sponges); reduced water quality (turbidity, eutrophication, sedimentation, low pH, algal blooms); declines in structural attributes (diversity, abundance, distribution, complexity, fragmentation); reductions in key functions or processes (photosynthesis, production, calcification, growth); higher prevalence of bleaching and diseases; and reductions in ecosystem resistance and resilience (i.e., the ability to absorb disturbances and the ability to bounce back after disturbances).

The principal threats to coral reefs and hardbottom communities of the Florida Keys marine waters occur mainly through the following pathways:

Coastal Development

The impacts of coastal development and the stressors created by associated activities (sedimentation, eutrophication, solid and chemical wastes, overexploitation, physical impacts) have been consistently ranked at the top of disturbance rankings with significant negative impacts on coral reefs and other coastal resources (Kleypas and Eakin, 2007; Waycott *et al.,* 2009). In the Florida Keys, impacts of population growth and an expanded need for both coastal and inland development on coral reefs and hardbottom communities are manifested mainly through the pathways or mechanisms listed below.

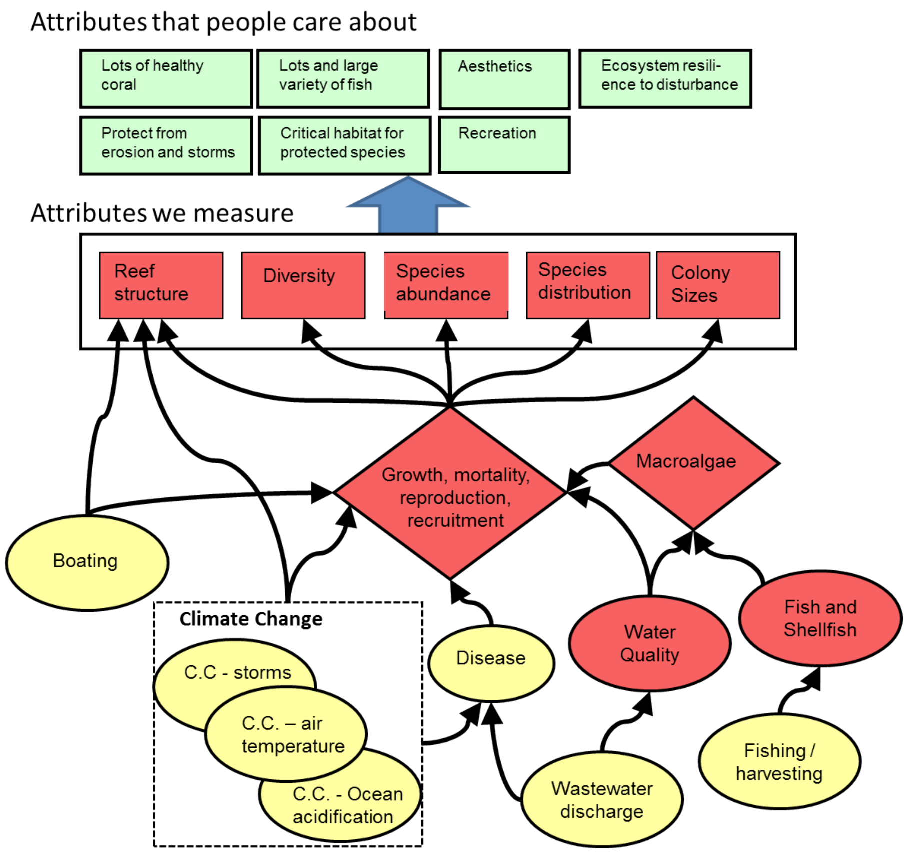

Figure 3. Coral and hardbottom submodel diagram for the Florida Keys/Dry Tortugas.

Fishing and Changes to Trophic Structure

Recreational and commercial fishing activities targeting coral reef and hardbottom communities provide a major economic driver in the Florida Keys. While the impacts of these activities on the fishery stocks are described in more detail in a separate conceptual model in this report, damage to benthic resources as a result of fishing and collection can also be considerable. These impacts generally fall into two categories: (1) changes to the trophic structure; and (2) physical impacts on benthic resources.

Corals and other slow-growing benthic organisms are in competition for limited space by faster growing macroalgae (Birrell *et al.,* 2008). Thus, any factor that favors macroalgal growth directly affects the growth and survivorship of corals (Steneck and Detheir, 1994). Overexploitation of fish stocks in the Caribbean has resulted in significant changes to the trophic structure of reef fish communities and a significant reduction in the abundance and size structure of populations of herbivorous fishes like parrotfishes (Hughes, 1994; Mumby, 2006). The reduction in grazing pressure and other factors like increased nutrients have prompted a phase in shifts on Caribbean reefs away from algal dominance towards algal-dominated states (Mumby, 2009). In Florida, grazing fishes are not targeted and are still abundant on Florida reefs. However, the major changes that have taken place over the last three decades may have limited their influence. The regional demise of the sea urchin, *Diadema antillarum*, as well as potential increased nutrient inputs from human activities, may have resulted in the present conditions of algal overgrowth that may be threatening some reef communities of the Florida Reef Tract (Carpenter, 1990; Lapointe and Clark, 1992; Szmant and Forrester, 1996; Lapointe, 1997; Bryant *et al.,* 1998).

The physical impacts of fishing and harvesting activities include the damage caused by ship groundings and propellers scars, as well as the damage caused by fishing gear such as lines, sinkers, traps, and trawler nets to benthic organisms like corals and sponges. In a study conducted in 2001, Chiappone *et al.* (2005) showed that lost hook-and-line fishing gear accounted for >85 percent of all debris encountered on Florida reefs and hardbottom communities and was responsible for >80 percent of the impacts to sponges and corals. The main impact of this type of gear consisted of tissue abrasion and partial or complete colony mortality. Similarly, considerable damage can be made to benthic resources by fishing gear targeting macroinvertebrates like lobsters and shrimp. Rogue lobster traps are often seen littering reefs after severe storms, and the long lines attached to these traps often cause severe abrasion to large coral colonies. The trawl nets used for the extraction of shrimp can also cause damage to sponges and soft corals on hardbottom habitats as shown in the study by Ault *et al.* (1997).

Changes in Water Quality

Pollutants

The location of Florida reefs adjacent to rapidly growing urban centers makes this unique system especially vulnerable to pollution commonly associated with coastal development and industrial, agricultural, and shipping activities. Contamination by pesticides, heavy metals, hydrocarbons, or other pollutants can significantly affect the health of reefs and other benthic communities. Heavy metals such as copper and zinc and some hydrocarbons have been linked to reduced fertilization, fecundity, and growth in corals and a large number of other reef organisms. Moreover, herbicides are known to cause physiological stress in corals even after short-term exposure at environmentally relevant concentrations. In addition, experiments conducted with fertilizers have shown that infection rates and the spread of coral diseases can be accelerated by increased concentrations of inorganic nutrients. Pathogens may also be introduced into the coastal environment through wastewater and groundwater releases.

Nutrients

At least part of the loss in coral cover recorded for the Florida Reef Tract in the recent past has been attributed to increased nutrient inputs from anthropogenic sources (Dustan and Halas, 1987; Lapointe and Clark, 1992, 1997; Porter *et al.,* 1999). Increased nutrient inputs into coastal habitats of Florida have been associated with activities such as coastal and upland development, water management practices, and stormwater runoff. Higher nutrient concentrations may affect corals directly by reducing calcification, growth, and fertilization rates (Fabricius, 2005) or indirectly favoring macroalgal growth, resulting in coral overgrowth, abrasion, and reduced recruitment (Tomascik and Sander, 1985, 1987; Kuffner *et al.,* 2006). A rapid increase in macroalgal abundance can cause severe degradation to reef communities and establish a persistent phase shift that delays or precludes the recovery of coral-dominated reef communities. Blooms of macroalgae (*Caulerpa brachypus*) and blue-green algae (*Lyngbya spp.*) have already been observed on reefs in South Florida and may, if persistent, result in such community shifts.

Increased nutrient levels can enhance phytoplankton production, increasing turbidity and reducing light penetration. Light reduction results in decreased photosynthetic yields in corals, while increased phytoplankton abundance may influence the activities of filter-feeding organisms such as sponges. Moreover, phytoplankton blooms can create anoxic or toxic conditions that may result in the mortality of both mobile and benthic reef organisms such as bivalves, sponges, and fish. Finally, several studies have documented increased abundances of reef bioeroders such as the boring sponge *Cliona spp.* and the bivalve *Lithophaga spp.* in response to enhanced nutrient availability. The activities of these bioeroders and coral competitors can cause reef communities to be more susceptible to physical disturbances such as storms and ship groundings.

Sedimentation

Around the world, water quality in coastal areas is changing in response to rapidly increasing coastal development and urbanization. Among the coral reef stressors commonly associated with these activities, sedimentation has been shown to be one of the predominant causes of reduced condition, abundance, and spatial extent of corals and other reef-associated organisms (Fabricius, 2005). In Florida, increased sedimentation has been associated with human activities such as port expansion, dredge-and-fill projects, coastal development, shoreline hardening activities, upland development, water management practices, and boating activities. Increased sediment loads can increase water turbidity, cause shading, smothering, and even burial of benthic organisms (Tilmant *et al.,* 1994; Te, 1997). Some of the effects commonly associated with high sedimentation include reductions in coral photosynthesis, growth, recruitment, and survivorship (Rogers, 1990).

Physical Impacts

Boating

The proximity of South Florida's reef resources to major ports, marinas, and shipping lanes, as well as the intense recreational and commercial boating activities that take place in the region, also means that benthic resources are especially vulnerable to physical impacts. The physical damage caused by ship and boat impacts include increased sedimentation, fragmentation of benthic organisms, detachment of sponges and coral colonies and, in the worst cases, the fracture or pulverization of the carbonate framework (Lirman *et al.,* 2010).

Storms

The impacts of storms on coral reefs and hardbottom organisms of the Florida Keys have ranged from minor (Manzello *et al.,* 2007) to severe (Lirman and Fong, 1997). The damage caused by storms includes breakage and fragmentation, abrasion, smothering, and burial (Fong and Lirman, 1995). In the most severe cases, portions of the reef framework can be dislodged during severe hurricanes (Gleason *et al.,* 2007).

Global Climate Change

Temperature Extremes

One of the most worrisome predictions of global climate change scenarios for coral reefs is the projected increase in seawater temperatures over the upcoming decades (IPCC, 2007). For coral reefs that are close to their thermal tolerance, increases in the intensity and frequency of warm-water anomalies can be catastrophic (Baker *et al.,* 2008). The most common response of corals to increased seawater temperature (commonly >30°C for extended periods) is bleaching, or the expulsion of their endosymbiotic dinoflagellates (zooxanthellae). The loss of zooxanthellae represents a serious energetic drain, as these microalgae provide their coral host with both nutrients and energy in the form of reduced carbon compounds. While bleaching is a reversible process, extended bleaching can cause significant coral mortality, as evidenced by the 2005 bleaching event that caused widespread mortality throughout the Caribbean region (Eakin *et al.,* 2010).

Finally, while high temperatures can impact corals directly, increased temperatures have also been correlated with a higher prevalence of diseases that can also cause significant coral mortality and would be an undesirable effect of global climate change in the Florida Keys (Brandt and McManus, 2009; Miller *et al.,* 2009).

Sea-Level Rise

Projected sea-level rise may influence both the condition of present coral reefs, as well as the future distribution of these communities. Changes in water depth can influence species distributions based on their specific light limitations and may limit the abundance of reef or hardbottom species with high light requirements (Hoegh-Guldberg, 1999). Communities and species living at their physiological depth/light limits will be most affected. Similarly, flooding of coastal habitats may increase inputs of sediment and nutrients with associated impacts on benthic organisms (as described in previous sections).

Ocean Acidification

With the realization that rising atmospheric carbon dioxide concentrations will cause changes in the ocean's carbonate chemistry leading to lower pH and lower saturation states of carbonate minerals, there is growing concern for marine organisms like corals that use such materials to build and support their skeletal structures (Kleypas *et al.,* 2006). Under global climate change scenarios, it is predicted that calcification rates will decrease up to 60 percent within the 21st century. The potential negative effects of acidification on corals include reduced fecundity, reduced larval settlement, reduced larval survivorship, reduced coral growth and calcification and, in the most extreme conditions, skeletal dissolution (Albright *et al.,* 2010; Albright and Langdon, 2011). Similar impacts are expected on other calcifying organisms like foraminifera, macroalgae, and macroinvertebrates. Limited information is presently available on the carbon chemistry of seawater on Florida reefs and hardbottom habitats.

Status and Trends

In Florida, documented rates of reef decline are similar to those reported by Gardner *et al.* (2003) for the entire Caribbean region. In the Florida Keys, coral cover has been lost at an average rate of 12.6 percent per year from 1996-1999 (Porter *et al.,* 2002). In addition to these declines in coral cover, declines in species richness of stony corals have also been recorded for the same time period. While patterns of coral decline have been certainly widespread, *Acropora spp.* and *Montastraea spp.*, the main reef-building taxa in Florida, have been especially impacted. For example, Miller *et al.* (2002) reported declines of 93 percent and 97 percent in the total live area of *A. palmata* and *A. cervicornis,* respectively, at Looe Key in the Lower Florida Keys between 1983 and 2000. A similar decline in the abundance of *A. cervicornis* (96 percent reduction) was reported by Jaap *et al.* (1988) at Molasses Reef in the Upper Florida Keys from 1981-1986. Dustan (1999) and Dustan *et al.* (2001) have also shown patterns of long-term declines in coral cover and condition at Carysfort Reef in the Upper Keys starting as far back as 1975. Lastly, steady declines in coral cover, especially on those sites dominated by *A. palmata,* were documented at permanent sites from Biscayne National Park to Looe Reef from 1984-1991 by Porter and Meier (1992) and from 1996 to 2000 by Patterson *et al.* (2002).

While the decline in coral condition may have started at least 20 years ago, more recent studies report a continuing decrease in coral abundance and diversity. For example, Porter *et al.* (2002) reported a decline in coral richness at 67 percent of permanent transects between 1996 and 2000 and a corresponding decline in coral cover of 38 percent over the same period. All sectors showed negative relative percent changes in coral cover between 1996 and 2000, but the Upper Keys experienced the most significant losses, with 72 percent of all stations reporting declines.

When patterns in coral cover from 1996-2009 for the Florida Keys were examined by the Coral Reef Evaluation and Monitoring Project (CREMP, http://ocean.floridamarine.org/fknms_wqpp/pages/cremp.html), consistent year-to-year declines were documented, with the biggest declines coinciding with the 1998 and 2005 coral bleaching events. The mean cover for all sites and habitat types recorded in 1996 was 12.7 percent and reached a minimum of 6.4 percent in 2006. However, since 1999, declines in coral cover have decreased in magnitude, and the first significant increase in coral cover (from 6.6 percent to 7.3 percent) was recorded between 2008 and 2009 (http://conference.ifas.ufl.edu/floridakeys/Presentations/Wednesday/PM/1415%20Ruzzicka%20R.pdf). Unfortunately, these positive trends were completely reversed by the cold-water anomaly that caused significant mortality to coral reefs in the Florida Keys in January 2010 (Lirman *et al.,* 2011).

Detailed information on the long-term condition patterns of hardbottom communities is generally lacking (but see Fourqurean *et al.,* http://serc.fiu.edu/seagrass/NearshoreWeb), and this clearly represents a knowledge gap for the system (Bertelsen *et al.,* 2009). Nevertheless, hardbottom communities have also experienced ecological declines in the recent past. One example is the mass mortality of sponges that was observed in Florida Bay and adjacent habitats in 1991. This decline was likely due to a bloom of cyanobacteria (Butler *et al.,* 1995).

Research and Knowledge Gaps

The coral reefs of the Florida Keys are one of the best studied ecosystems in the world. Long-term monitoring programs and scientific research have provided ample documentation on the status and trends of these resources, especially within the last 20 years. Some future research priorities and gaps include:

Improved Knowledge of Status and Trends of Hardbottom Habitats

Increased understanding of the factors influencing the abundance and distribution of hardbottom organisms. Hardbottom communities have received comparatively less attention than coral reef habitats and thus research and monitoring in these habitats is lagging behind that in offshore coral reefs. Spatial gaps in knowledge are especially evident for hardbottom habitats of north Key Largo and Biscayne National Park.

Genetic Connectivity of Coral Populations

While the connectivity of fish populations in the Florida Keys has received some attention, limited knowledge presently exists on the genetic connectivity of coral populations in the Florida Keys (with the exception of populations of *Acroporid* corals). Information is needed on the connectivity among regions, as well as between shallow and deep habitats that may serve as refuge from thermal anomalies.

Mesophotic Reefs

At present, only limited information is available on the abundance, distribution, diversity, and condition of coral from mesophotic reefs (>30 m in depth and characterized by a low availability of light). These habitats may prove to be important spawning grounds for commercial and recreational reef fish species like groupers and may also play a role as refuges from extreme environmental disturbances like temperature anomalies and storms.

Impacts of Everglades Restoration on Hardbottom and Coral Reef Habitats

While some adverse impacts related to changes in hydrology have been documented for hardbottom habitats (i.e., cyanobacterial blooms that cause sponge mortality), the potential future impacts of the changes in the freshwater delivery patterns into coastal bays are presently unknown. To document and predict such changes, especially those related to changes in salinity and nutrient content, additional research focused on nearshore hardbottom and coral reef habitats is needed.

Impacts of Ocean Acidification

While the impacts of seawater temperature anomalies on corals and other benthic organisms have been well documented, research on the impacts of ocean acidification on coral reefs and hardbottom habitats of the Florida Keys is still in its infancy. Additional research is needed to document present carbonate chemistry on these habitats and potential impacts of reduced calcification scenarios on corals and other calcifying organisms like macroalgae, urchins, and gastropods.

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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 the bottom from recreational and commercial activities in seagrass beds can lead to complete loss of seagrass beds from heavily affected areas.
- Eutrophication of coastal waters, often related to increasing human development, has been implicated in the loss of seagrasses in many areas of the world, including South Florida.

There are few places on earth where seagrass beds are as expansive as the nearshore marine ecosystem of South Florida. With 14,622 km^2 of seagrasses in South Florida, this area ranks among the most expansive documented 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). Accordingly, the economic impact and ecological importance of the South Florida seagrass beds are significant (Zieman, 1982). Over half of all employment in the Florida Keys is dependent on outdoor recreation (NOAA, 1996). For the larger part, these outdoor activities rely on the clear waters and healthy marine habitats in the nearshore marine environment. Fisheries landings in the Florida Keys total over 12×10^6 kg annually of mostly seagrass-associated organisms (Bohnsack *et al.,* 1994).

Five species of rooted aquatic vascular plants, or seagrasses, are commonly found in South Florida: *Thalassia testudinum, Syringodium filiforme, Halodule wrightii, Halophila decipiens,* and *Ruppia maritima*. One additional species, *Halophila johnsonii,* occurs in the extreme northern Biscayne Bay and India River Lagoon. Seagrass communities are found from the mangrove-lined estuaries of Florida Bay, the Shark River drainage, and the Ten Thousand Islands out to back-reef environments and open continental shelf waters (Figure 1). T. testudinum is often dominant in areas of stable salinity and stable sediments. *H. wrightii* and *S. filiforme* are often found in deeper water and areas that are more frequently disturbed, and the *Halophila* species are generally restricted to low-light environments (<15 percent of surface irradiance) and turbid shallow waters. In general, *R. maritima* is restricted to areas near freshwater sources. The total seagrass habitat in the South Florida region covers least 17,620 km^2 of semicontinuous beds.

Seagrasses Support Fisheries and Maintain Water Quality

Most of the value of commercial fisheries landings in the Florida Keys comes from either seagrass resident species (e.g., pink shrimp) or from species that rely on seagrasses

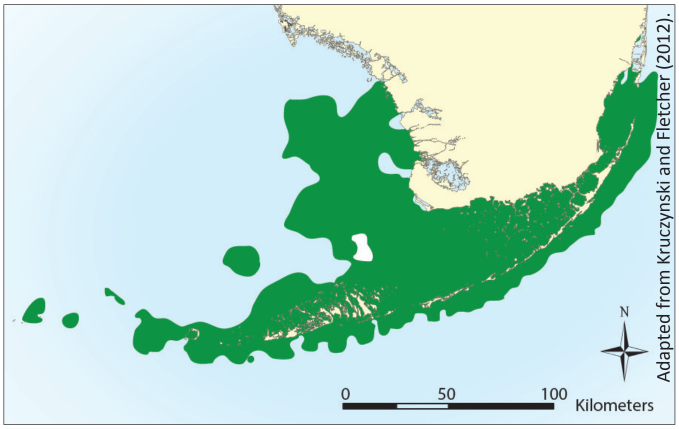

Figure 1. Distribution of seagrass beds in the Florida Keys marine ecosystem.

for nurseries for their early life stages (e.g., Caribbean spiny lobster, grouper). We know of no assessments of the commercial value of commercial landings of seagrass-dependent species in South Florida, but one study from subtropical Australia concluded that the fisheries value of seagrass beds was $3,500 per hectare per year (Watson *et al.,* 1993). Extrapolating this areal value to the extent of seagrasses in South Florida results in a potential fisheries value of $6.3 billion per year. Seagrass beds are recognized as among the most productive (Zieman and Wetzel, 1980) and economically valuable (Costanza *et al.,* 1997) of ecosystems, and the economy of the Florida Keys is inextricably tied to seagrass beds and other nearshore benthic marine habitats. 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).

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 dieoff 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 dieoff (Boyer *et al.,* 1999). This decrease in water clarity led to a further decline and change in community composition of the seagrasses that survived the dieoff (Hall *et al.,* 1999). Such a change in state is reminiscent of the multiple stable states experienced by some lakes that alternate between multi-year periods of clear water and high benthic vegetation abundances and multi-year periods of very turbid water and no benthic vegetation (Scheffer *et al.,* 2001). If such large-scale losses of seagrasses occurred throughout the Florida Keys, the degradation in water quality would undoubtedly have severe impacts on the coral reefs of the region, which surely would not survive a multi-year stable state of the coastal waters of the Florida Keys dominated by high turbidity and abundant phytoplankton.

Attributes People Care About

Seagrasses in the Florida Keys support attributes of the marine environment that people care about. These attributes are directly related to ecosystem services provided by the Florida Keys marine ecosystem:

- Abundance 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

Abundance and Large Variety of Fish

Seagrass beds are important locations for recreational fisherman in the Florida Keys. 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. Further, the guided fishing charter industry in the Florida Keys is largely dedicated to taking customers to seagrass ecosystems to catch game fish including tarpon, permit, bonefish and snook, all seagrass-resident species.

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. An example of the importance of seagrasses for protecting against sediment resuspension and erosion was provided when a large area of seagrass meadows north of Marathon were overgrazed by sea urchins in the late 1990s. Following the overgrazing, 5-10 cm of sediment was lost and algae in the water column tripled (Peterson *et al.,* 2002).

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 like cycle, including Caribbean 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 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 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 ranges (95 percent c.l. of mean values) from 20.73-101.39 Tg C yr^{-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 1.2-3.0 Tg C yr^{-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

The U.S. EPA established a monitoring program in 1995 designed to define the status and trends of seagrass communities in the Florida Keys National Marine Sanctuary (FKNMS) as part of the agency's comprehensive Water Quality Protection Plan for the sanctuary (Fourqurean and Rutten, 2003). The monitoring program addresses concerns over eutrophication and its impact on the status of seagrass communities in the FKNMS. The monitoring program was designed to determine regional-scale gradients in the status of seagrass by compiling data on these attributes of the seagrass beds:

- Spatial extent
- Depth distribution
- Biomass
- Species composition
- Elemental and isotopic composition
- Genetic diversity

Each of these parameters can be explicitly linked to environmental factors of known management concern and are explicitly linked to the structure and function of seagrass meadows.

Spatial Extent

In many coastal ecosystems, the interaction of the high light requirement of seagrasses, water clarity, and water depth control the spatial extent of seagrass ecosystems. For example, in Tampa Bay, the areal extent of seagrasses shrank by 70 percent in the 1960s and 1970s in response to decreases in water clarity. Subsequent improvements to wastewater treatment led to a partial recovery of the lost seagrasses as water quality improved (Greening and Janicki, 2006). Seagrass beds can also shrink from the deliberate or accidental destruction of the habitat. Dredging and filling of seagrasses for coastal construction and navigation were commonplace prior to the 1960s (Short and Wyllie-Echeverria, 1996), and repeated erosion caused by acute vessel groundings and chronic "prop scarring" by boats operating in shallow water continues to result in large decreases in the areal extent of seagrasses (Sargent *et al.,* 1995).

Depth Distributions

As a group, seagrasses have a very high requirement for light compared to other plants growing in low-light environments. This is likely because of the large proportion of seagrass biomass that is buried in the sediment as root and rhizome tissues, the general scarcity of oxygen in marine sediments in which those below-ground tissues are buried, and the absorption of light by sediments and organisms that foul the seagrass leaves. Where both phytoplankton, macroalgae, and typical terrestrial shade-adapted plants require less than 1 percent of incident sunlight to thrive, seagrasses require 10 percent or more (Duarte, 1991). Note, however, that there are important species-specific differences in light requirements among the seagrasses common in South Florida. *T. testudinum* requires more light and, therefore, is restricted to shallower locations than either *H. wrightii* or *S. filiforme* (Wiginton and McMillan, 1979), and the species of *Halophila* that occur in South Florida require even less light (about 5-8 percent of surface irradiance in South Florida, J.W. Fourqurean, unpublished data).

Biomass

The biomass of seagrasses is a function of the supply of the necessary resources for seagrass growth (most importantly, light and nutrients), as well as the loss rate of seagrass leaves (both due to physical processes and herbivory) and environmental conditions like temperature and salinity. In the very nutrient-poor areas of South Florida, an increase in nutrient availability leads to an increase in biomass of the seagrass beds (Fourqurean *et al.,* 1992b; Ferdie and Fourqurean, 2004; Armitage *et al.,* 2005). As the habitat value of the seagrass bed is partially a function of the biomass of the seagrasses, changes in biomass will affect the animals resident in the seagrass beds and the structure of the food webs they support (Hemminga and Duarte, 2000; Gil *et al.,* 2006).

Species Composition

Knowledge of the species composition and their relative abundance, and how these factors change in time, provides an insight into the ecological health of seagrass meadows. The pattern of the anthropogenically-driven loss of seagrass beds across the globe leads to a generalized model of the effects of nutrient loading on seagrass beds (Duarte, 1995). In general, eutrophication in aquatic environments shifts the competitive balance to faster-growing primary producers. The consequence of this generality in seagrass-dominated environments is that seagrasses are the dominant primary producers in low-nutrient conditions. As nutrient availability increases, there is an increase in the importance of macroalgae, both free-living and epiphytic, with a concomitant decrease in seagrasses because of competition for light. Macroalgae lose out to even faster-growing microalgae as nutrient availability continues to increase: first, epiphytic microalgae replace epiphytic macroalgae on seagrasses; then planktonic microalgae bloom and deprive all benthic plants of light under the most eutrophic conditions.

Using knowledge of the life history characteristics of local species and experimental and distributional evidence, this general model can be adapted to seagrass beds of South Florida. The South Florida case is more complicated than the general case described above because there are six common seagrass species in South Florida, and these species have different nutrient and light requirements; hence, they have differing responses to eutrophication. Large expanses of the shallow marine environments in South Florida are so oligotrophic that biomass and growth of even the slowest-growing local seagrass species, *T. testudinum*, are nutrient-limited (Fourqurean *et al.,* 1992a; Fourqurean *et al.,* 1992b). At this very oligotrophic end of the spectrum, increases in nutrient availability actually cause increases in seagrass biomass and growth rate (Powell *et al.,* 1989). As nutrient availability increases beyond what is required by a dense stand of *T. testudinum*, there are other seagrass species that will out-compete it. At locations with more constant marine conditions, there is evidence that *S. filiforme* may be a superior competitor to *T. testudinum* in areas of enhanced nutrient availability (Williams, 1987).

In estuarine areas of South Florida, nutrient addition experiments show that *H. wrightii* will prevail over *T. testudinum* under fertilized conditions (Fourqurean *et al.,* 1995). Evidence from the distribution of primary producers around point-sources of nutrient input show that in estuarine areas there are zones of dominance of different species with respect to nutrient availability, from *T. testudinum* at lowest nutrient availability, to *H. wrightii* at higher availability, to *Ruppia maritima* at higher availability, followed by a microalgae-dominated zone at highest nutrient availabilities (Powell *et al.,* 1991). The abundance of macroalgal epiphytes also increases along the same gradient, up until the point that microalgae become dominant (Frankovich and Fourqurean, 1997). Consequently, the relative importance of the various primary producers can be used to assess the trophic state of the community (Fourqurean and Rutten, 2003). Trends towards dominance by faster-growing species and a decrease in the dominance of slow-growing turtlegrass indicate increases in nutrients, driving a change in seagrass meadows.

Elemental and Isotopic Composition

Tissue nutrient concentrations can be monitored to assess the relative availability of nutrients to the plants. For phytoplankton communities, this idea is captured in the interpretation of elemental ratios compared to the familiar "Redfield ratio" of 106C:16N:P (Redfield, 1958). Similar analyses can be made with data from seagrasses and macroalgae with the recognition that the taxon-specific "Redfield ratio" may be different from the phytoplankton ratio (Atkinson and Smith, 1983; Duarte, 1992; Gerloff and Krombholtz, 1966). For the seagrass *T. testudinum*, the critical ratio of nitrogen:phosphorus (N:P) in green leaves that indicates a balance in the availability of N and P is ca. 30:1, and monitoring deviations from this ratio can be used to infer whether N or P availabilities are limiting this species' growth (Fourqurean *et al.,* 2005). Hence, *T. testudinum* is likely to be replaced by faster-growing competitors if nutrient availability is such that the N:P ratio of its leaves is ca. 30:1. A change in the N:P ratio in time to a value closer to 30:1 is indicative of increased nutrient availability or decreased light availability. The spatial pattern in the N:P ratio can be used to infer sources of nutrients for supporting primary production in the ecosystem (Fourqurean *et al.,* 1997; Fourqurean and Zieman, 2002; Fourqurean *et al.* 1992a).

In addition to elemental stoichiometry, ratios of the stable isotopes of carbon and nitrogen have proven useful indicators of the supply and processing of nutrients. Stable isotope ratios in macrophytes and consumers have proven valuable in tracing the flow of energy in marine food webs (Peterson *et al.,* 1985; Peterson, 1999). Stable isotope ratios can also be used to identify nutrient sources and processing in ecosystems. For example, 13C/12C ratios in macrophytes have been used to identify the importance of allochthonous carbon to marine ecosystems (Zieman *et al.,* 1984; Lin *et al.,* 1991; Hemminga *et al.,* 1994). Since discrimination against uptake of 13C is partly a function on the demand for CO_2 used in photosynthesis, there is a relationship between the stable C isotope content of seagrasses and the amount of light that reaches the plants, with isotopically lighter tissues resulting from low light (Grice *et al.,* 1996).

Bacterially-mediated processing of N can strongly influence stable N isotope ratios and, as a consequence, the spatial pattern in 15N/14N ratios in macrophytes can be used to infer ecosystem-scale processing of organic matter (Fourqurean *et al.,* 1997). Carbon and nitrogen isotopes have been used in both paleoceanography and paleolimnology to infer changes in water column nutrient cycles (e.g., Schelske and Hodell, 1991). Owing to the isotopically heavy N associated with many anthropogenic nutrient sources, stable isotopes of N in macrophytes are potentially invaluable tools for gauging the impact of man on coastal water bodies (McClelland and Valiela, 1998a, 1998b). This tool is potentially of primary importance because of the magnitude of the impact man is having on coastal water bodies through anthropogenically-increased N loading (Paerl, 1997; Vitousek *et al.,* 1997; Tilman *et al.,* 2001).

Genetic Diversity

The genetic diversity of seagrasses can have important ecological consequences for seagrass ecosystems (see Hughes *et al.,* 2008 for a review). For instance, genetically-diverse plant populations can be more successful at reproducing (Ellstrand and Antonovics, 1985; Johnson *et al.,* 2006). In addition, genetic diversity can increase the habitat value of seagrass meadows by increasing the diversity and abundance of associated invertebrates (Hughes and Stachowicz, 2004; Reusch *et al.,* 2005). Furthermore, genetic diversity can increase the stability of systems and enhance resistance to or recovery from disturbance (Hughes and Stachowicz, 2004). In this way, genetic diversity is an important determinant of the way seagrass ecosystems can respond to anthropogenic and natural pressures on the ecosystem.

Light penetration through the water column is a function of the amount of particulate and dissolved substances in the water, two important aspects of water quality that affect seagrass resources. As water clarity decreases, seagrass depth distributions will also decrease. Additionally, nutrient availability has a direct impact on seagrass light requirements and, therefore, depth distribution that is independent of its influence on water clarity. High nutrient availability leads to epiphyte overgrowth of seagrass leaves (Tomasko and Lapointe, 1991). These epiphytes directly block light from seagrass leaves (Frankovich and Zieman, 2005).

Drivers of Change in Seagrass Beds

Pressures affecting seagrass beds in the Florida Keys marine ecosystem can be traced to two sets of drivers: near-field drivers that act within the region of the Florida Keys and Dry Tortugas and far-field drivers that operate at regional and global scales Near-field drivers include fishing and other, more general effects of development of the Keys on the surrounding waters. Far-field drivers include regional inputs of nutrients, which contribute to a general increase in nutrient concentrations in the coastal ocean, climate change, and the effects of rising carbon dioxide concentrations on ocean water chemistry. While climate change and changes to ocean water chemistry are of concern, their current impact on seagrasses in the Florida Keys is probably not as large as the other drivers of change, like water quality degradation and direct removal of seagrasses due to boat groundings and propeller scarring.

Fisheries, Species Extinction, and Changes in the Food Web

While the net effect of humans altering food webs is not certain, in all likelihood our current seagrass ecosystems are different now than they were before human alteration of coastal food webs through selective harvesting of the large predators and herbivores from the ecosystem. Humans have been harvesting food from the ocean for millennia. Besides the impacts on populations of currently targeted species detailed in the Fish and Shellfish ICEM submodel, the systematic depletion of larger-bodied organisms by humans has drastically altered food webs in the world's oceans (Jackson, 2001; Jackson *et al.,* 2001; Baum *et al.,* 2003; Myers and Worm, 2003). These altered food webs can change the functioning of coastal ecosystems (Worm *et al.,* 2000) and can even have effects that cascade downward to the structure of the seagrass beds (Jackson, 2001). The loss of top predators, like sharks and large groupers, may increase the population of smaller herbivores, resulting in more grazing of seagrass beds. Given that these smaller herbivores exhibit a preference for fast-growing, high nutrient-content seagrasses, changes in predators could result in a change in species composition of the seagrass beds (Armitage and Fourqurean, 2006). In contrast, the marked population reductions of large herbivores, like green sea turtles and manatees from pre-Columbian times, may have resulted in a decrease in grazing and an overgrowth of seagrasses beyond their historic extent (Jackson, 2001).

There is also the possibility that fisheries activities that lead to the loss of filter feeding organisms, like sponges and mussels, could negatively affect seagrasses. The loss of the filtering activity of these organisms can lead to decreases in water clarity. Such a cascade of effects has been hypothesized as an important driver behind seagrass losses in Florida Bay in the late 1980s and early 1990s where blooms of noxious blue-green algae caused the death of most of the sponge community in western Florida Bay (Butler *et al.,* 1995). The subsequent loss of sponge filtration decreased the effective time required for sponges to filter the water column of Florida Bay (Peterson *et al.,* 2006).

Coastal Development

Urban/suburban development of the Florida Keys 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 losses, but 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 Florida Keys 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 the 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 a 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 Salinity and Temperature

Increasing sea surface temperatures may negatively impact seagrasses in the region. This point was illustrated by the loss of the 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 the salinity climate, with increases in the amount and variability in runoff leading to a change from *T. testudinum*-dominated seagrass beds to ones dominated by *H. wrightii* (Fourqurean *et al.,* 2003). Anthropogenic decreases in freshwater flow into Florida Bay played a major role in the shift of the seagrass communities of eastern Florida Bay from a *H. wrightii*-dominated state in the 1970s to a *T. testudinum*-dominated state in the 1980s (Schmidt, 1979; Zieman, 1982).

Mechanisms of Change in Seagrass Beds

The principal threats to seagrass beds in Florida Keys marine waters occur through three pathways: eutrophication of the normally oligotrophic Keys marine waters; changes in the food-web; and damage to seagrass beds as the direct result of human activities (Figure 2).

Eutrophication

Three sources of nutrients alter water quality in Florida Keys marine waters and potentially fuel eutrophication. Storm water runoff and domestic and municipal wastewater affect water quality in inshore waters, especially inshore areas like canals, that are poorly flushed by tides. Increased nutrient loads in freshwater inflow from mainland watersheds are another source of increased nutrient concentration in Florida Keys waters. Increased nutrient loads to Florida Shelf waters are the result of changing land use and agricultural practices both in the South Florida region and beyond.

Nutrient loading from both wastewater and stormwater in the Florida Keys has a high potential to negatively affect seagrass beds. The natural state of the nearshore marine waters is one of nutrient limitation of plant (and therefore animal) biomass. The addition of nutrients to the system causes an increase in total plant biomass and a shift in species composition. At the natural low-nutrient state, slow-growing species like *T. testudinum* are the competitively dominant species but, as nutrient availability increases, the competitive dominance shifts to successively faster-growing species. At the highest nutrient loads, phytoplankton, the fastest-growing primary producers, cloud the water and decrease the penetration of light through the water to the bottom, effectively shading out seagrasses and benthic macroalgae.

Changes to the Food Web

While the net effect of humans altering food webs is not certain, in all likelihood our current seagrass ecosystems are different now than they were before human alteration of coastal food webs through selective harvesting of the large predators and herbivores from the ecosystem, as discussed previously.

Damage—Benthic Community

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 Jonge, 1992). In South Florida, the offshore waters that support the Tortugas shrimp fishery are underlain by extensive meadows of the seagrass *H. decipiens* (Fourqurean *et al.,* 2001). 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 beneath them. Storms can drag these traps around the bottom, magnifying 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 has been largely 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 within an order of magnitude (Duarte, 2002). In Florida, anthropogenic seagrass losses 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 a loss of seagrasses in the study area (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

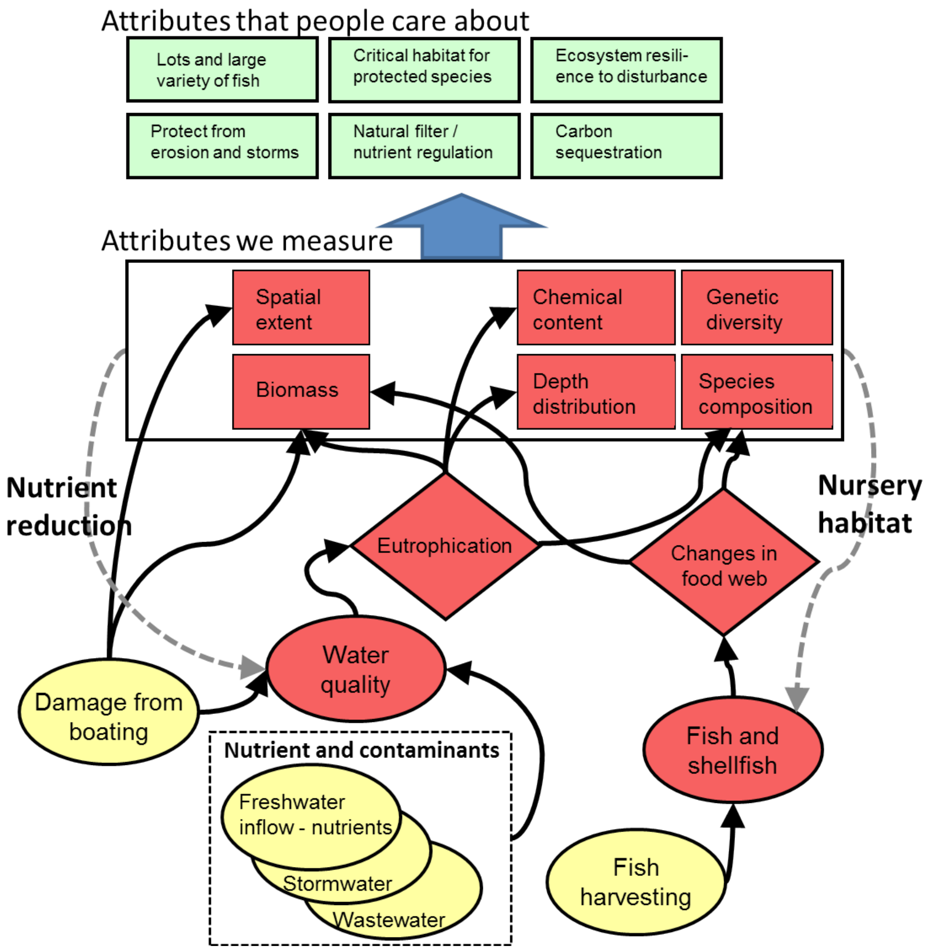

Figure 2. Seagrasses submodel diagram for Florida Keys and Dry Tortugas.

followed the loss of seagrasses (Phlips 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).

While the history of seagrass trajectories in the coastal zone worldwide and in Florida, in particular, is not good, there are some indications that some of these trajectories are reversible. For example, six years after the implementation of sewage collection and treatment and the cessation of the use of septic tanks and cesspits in the Marathon Key area, there are indications that seagrass declines can be reversed (Herbert and Fourqurean, unpublished data). Elemental content and stable carbon isotope ratios indicate a decrease in eutrophication and an increase in light reaching the seagrass meadows nearest the shoreline. Because of the very long residence time of the nutrient phosphorus in seagrass meadows of the Florida Keys (Herbert and Fourqurean, 2008), the species composition of these seagrass beds has yet to revert to the more slow-growing species, but it is expected that this will occur over the next decade.

Topics of Scientific Debate and Uncertainty

While historic changes have elucidated the pathways by which ecosystem structure and function change in response to increased human pressure, we do not have a good idea what pathways these seagrass ecosystems will follow once the human pressures have abated. We know, for instance, that the primary limiting nutrient for most of the region, phosphorus, has a very long residence time in seagrass meadows in South Florida. Understanding the factors controlling the loss of phosphorus from eutrophied systems is critical to projecting pathways of recovery. Further, research is needed on how effective habitat restoration efforts are towards restoring seagrass ecosystem structure and function. We also need a better understanding of how food web alteration has affected the structure and function of seagrass meadows to understand how current fisheries practices and conservation efforts are likely to affect seagrass meadows in the future. For example, it appears that resurgent green sea turtle populations in Bermuda, in the absence of top predators to control their populations, may be contributing to the loss of seagrass beds in that country (Fourqurean *et al.,* 2010). Without a full understanding of food web structure in our coastal systems, there could be unintended consequences in our fisheries and conservation strategies.

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Benthic Habitat: Mangroves

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In a nutshell:

- The mangrove forests of the Florida Keys and Dry Tortugas 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 in the Florida Keys has been destroyed largely by urbanization of the Keys from the late 1950s through the 1980s. The large-scale loss of mangroves has all but ceased in the Keys due to laws protecting wetlands; however, these laws are continuously under threat of being relaxed. Other localized threats are contaminant spills and invasive species.
- Climate change is the largest global threat to mangroves of the Florida Keys and Dry Tortugas. 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 in the FK/DT (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 the loss of this habitat in the Florida Keys. 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 in the Florida Keys: 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.

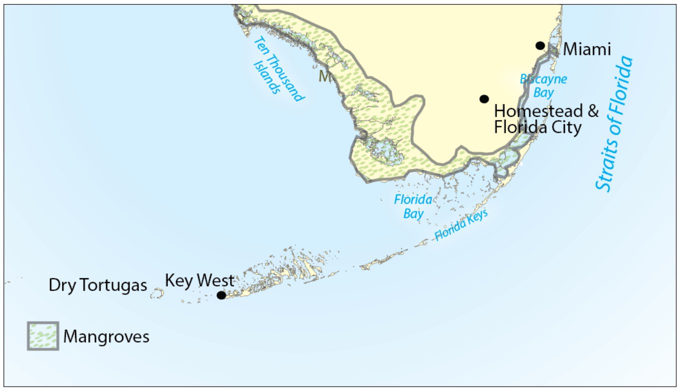

Figure 1. Mangrove forests in the Florida Keys and Dry Tortugas.

Role of the Mangroves in the Ecosystem

Mangrove forests can sequester nutrients and act as a wastewater filter (Ewel *et al.,* 1998), thereby playing a role in water quality, and they are sources for the export of organic material into coastal waters (Lugo and Snedaker, 1974; Odum and Heald, 1975; Twilley, 1985, 1988; Nixon, 1980). 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 Florida Keys/Dry Tortugas 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 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).

Attributes People Care About

The mangroves of the FK/DT provide critical *Ecosystem Services* to the entire southwest coastal ecosystem including:

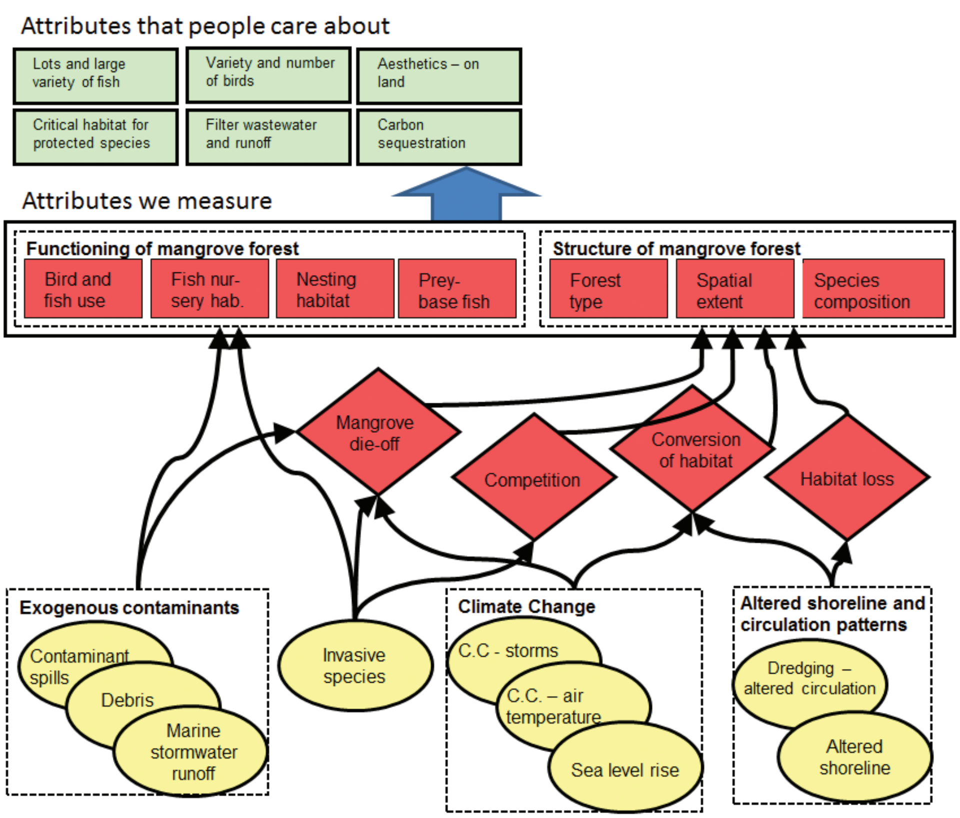

Figure 2. Mangroves submodel diagram for the Florida Keys and Dry Tortugas.

- 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 in the Florida Keys 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 for 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 Florida Keys (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 previously, 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. Back-country 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 Florida Keys (pink shrimp, Caribbean spiny lobster, and stone crabs) also spend portions of their juvenile life stages in mangrove forests (Lewis *et al.,* 1985).

Aesthetics

Leeworthy and Wiley (1996) surveyed residents and visitors of the Florida Keys 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.

Natural Filter for Wastewater and Storm Runoff

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 storm water are rich in these nutrients, which can be damaging to coral reefs and other ecosystems (see water quality and coral-hardbottom submodels). The presence of mangroves adjacent to developed areas of the Florida Keys 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 storm water runoff and can be damaging if they enter the various food webs of the Florida Keys.

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, the 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 in the Florida Keys. Losing more mangrove habitat could further endanger these species, lowering biodiversity and also making the Keys 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.

Source 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 Florida Keys) 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 in the Florida Keys 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 Florida Keys/Dry Tortugas 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 Tree Species Composition

Mangrove forests of the Florida Keys were destroyed in large numbers during the development boom from the late 1950s to the early 1980s (Strong and Bancroft, 1994; Lorenz *et al.,* 2002). Currently, mangrove habitats are protected in the Keys, 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. Hiwstorically, 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 in the Florida Keys 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 performed 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 in the Florida Keys 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 FK/DT 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 FK/DT.

Drivers of Change in Florida Keys/Dry Tortugas Mangrove Forests

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 Florida Keys 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 (Figure 2). 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 Florida Keys, 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 Florida Keys 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). Storm water runoff may contain petroleum products or other contaminants that may also be injurious to mangrove trees in urbanized areas of the Florida Keys. 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 in the Florida Keys 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 levels rise (Davis *et al.,* 2005). This may not be possible in the Keys, as much of the 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 a greater frequency and intensity of strikes in the Florida Keys. As was demonstrated from Hurricane Andrew in 1992, intense storms can destroy entire mangrove forests (Pimm *et al.,* 1994). The interaction of increased hurricane activity and 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 in the Florida Keys 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 Florida Keys (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 in the Florida Keys 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 roadbed (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 reefs 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.,* 2000), 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 Florida Keys could result in an oil spill that reaches and destroys these mangroves.

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 cannot 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 in the Florida Keys, 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, 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, Upper and Lower Matecumbe Keys, respectively. Although current and future losses of both mangrove and upland habitat in the Florida Keys 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 in the Florida Keys 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). In the Florida Keys, 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 Florida Keys 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).

As stated above, 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 (U.S. Army Corps of Engineers, 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 in the Florida Keys 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 in Florida Keys 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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