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

MARine Estuarine goal Setting (MARES) for South Florida

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Preface

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

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

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

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

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

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

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

Table of Contents

Table of Contents (continued)

Appendices

Figures

Tables

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.

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 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.

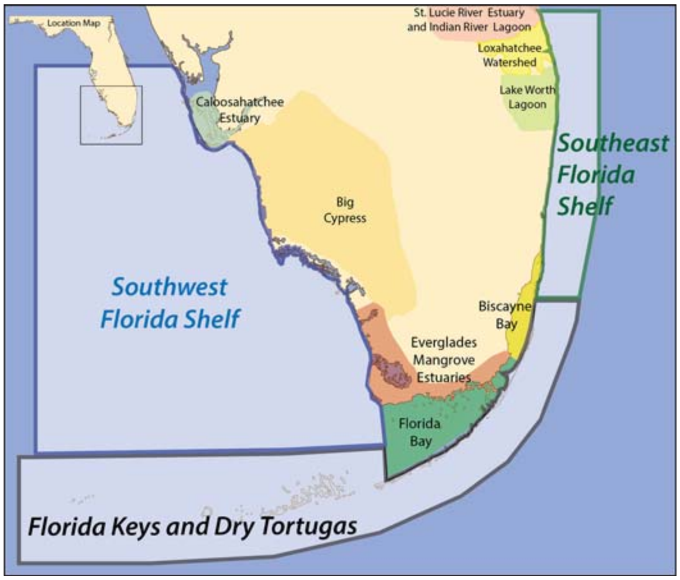


Figure 1. Map of the South Florida coastal marine ecosystem and three MARES subregions.

Each subregion exhibits distinct geomorphic and oceanographic characteristics. The SWFS encompasses the broad, shallow Florida Shelf. 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).

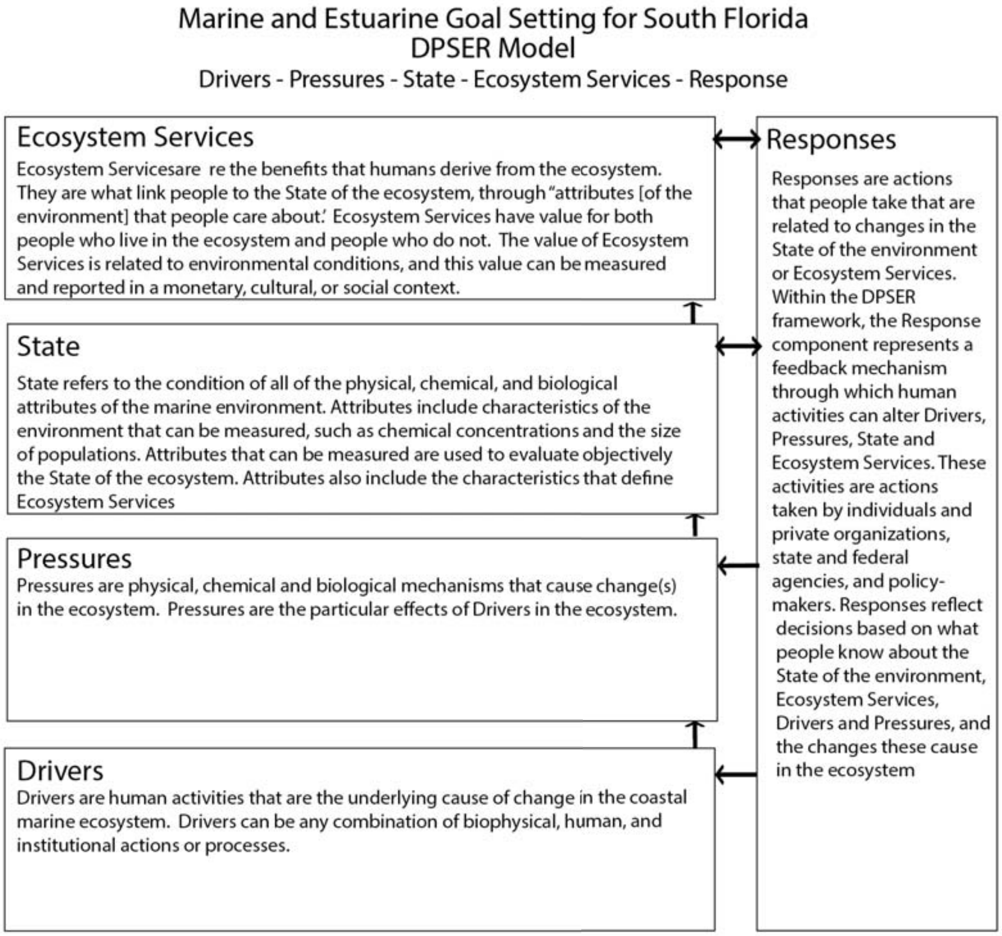
The second step is to build upon these diagrams to develop ICEMs. This process is then repeated for each of the three subregions. The ICEMs serve as the basis for synthesizing our scientific knowledge. They also help complete the third and final step to identify subregional indicators, QEIs (both societal 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



Ecosystem Services

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

State

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

Pressures

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

Drivers

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

Responses

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

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

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.

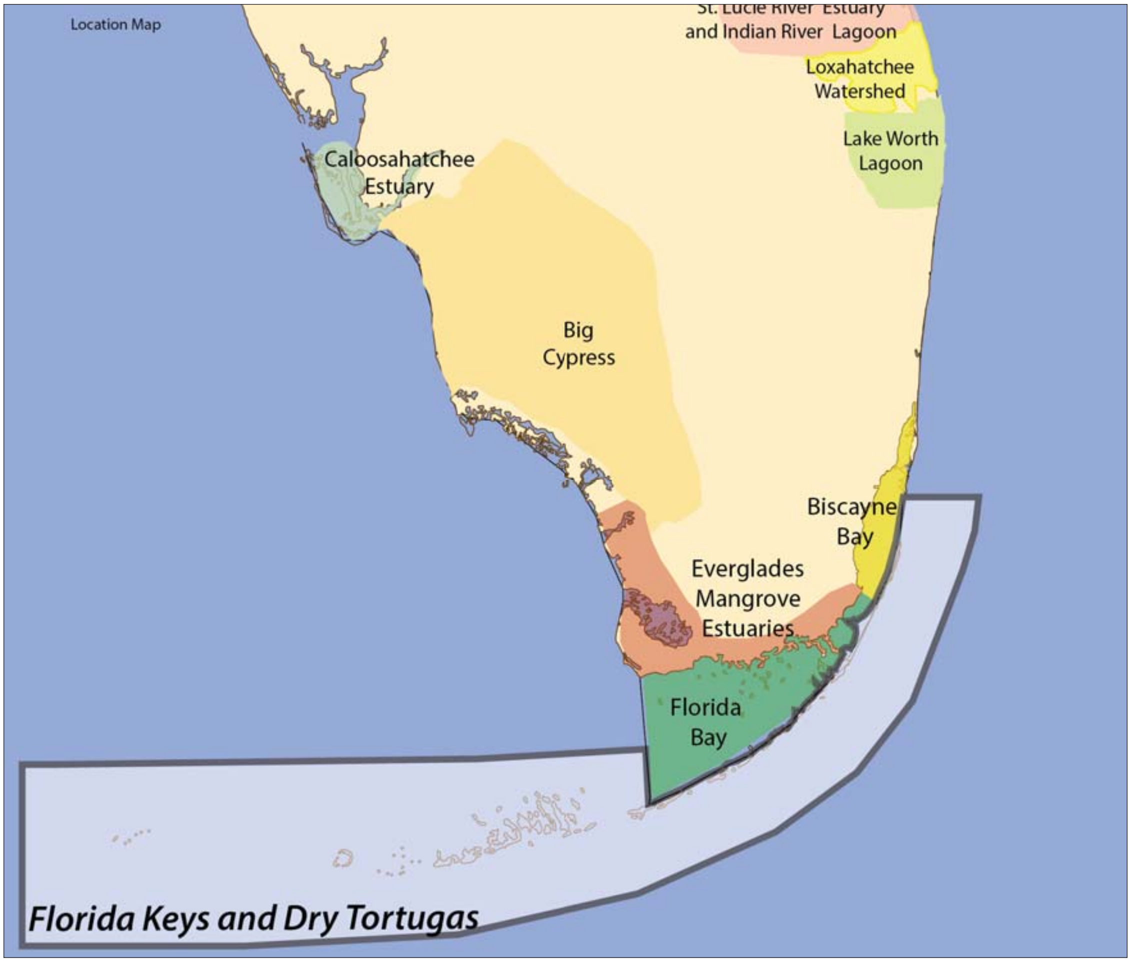


Figure 4. The Florida Keys are comprised of a chain of developed islands stretching from Key Largo to Key West that continue westward to the Dry Tortugas National Park, a chain of undeveloped islands.

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**).

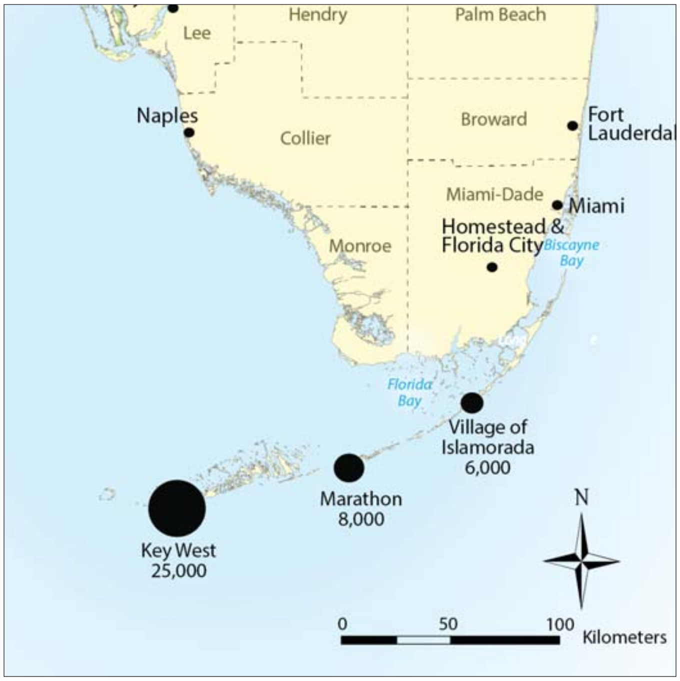


Figure 5. Population centers in the Florida Keys (Bureau of Census, 2010).

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 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).

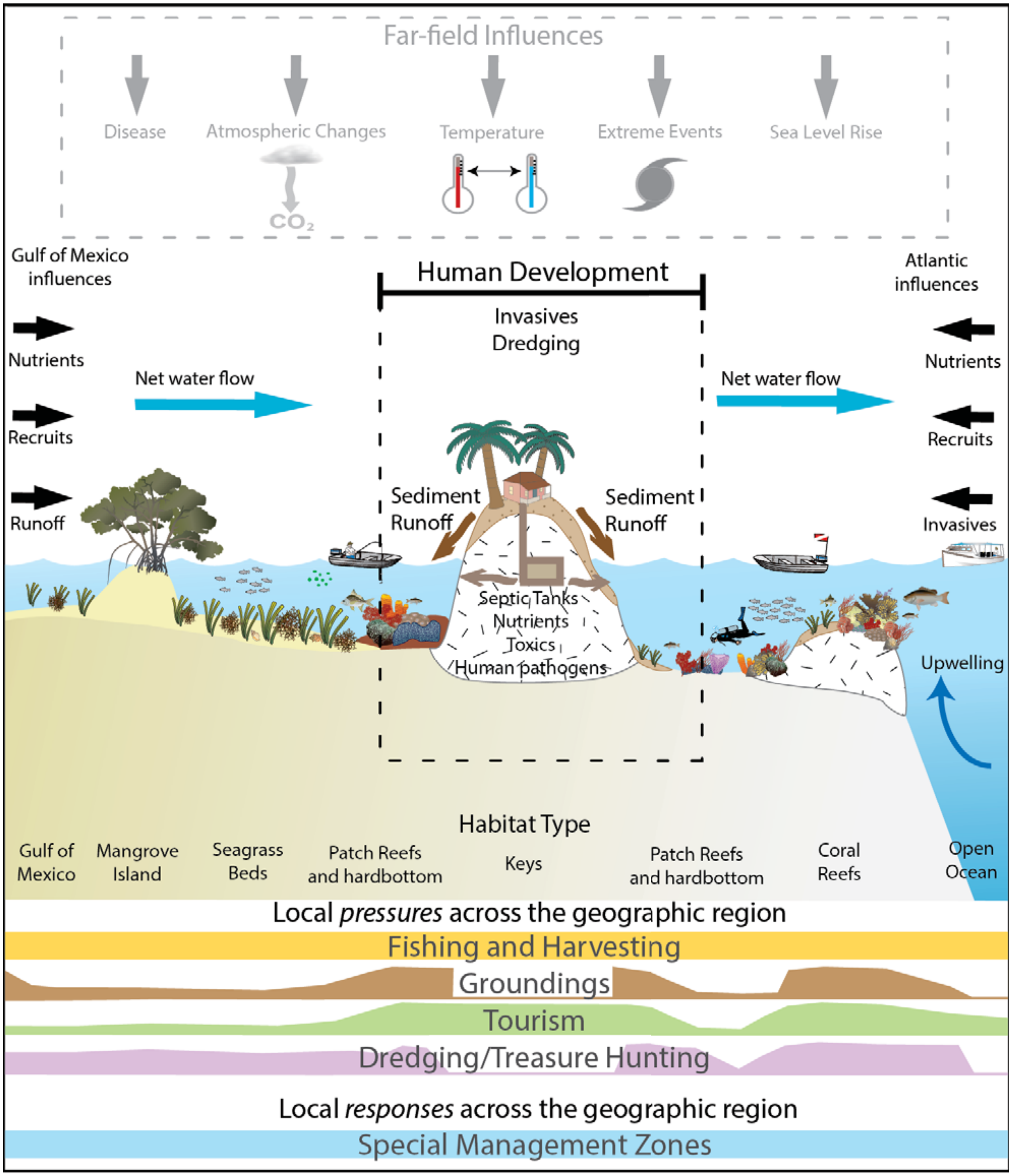


Figure 6. The Florida Keys/Dry Tortugas and the factors affecting their condition.

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.

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-

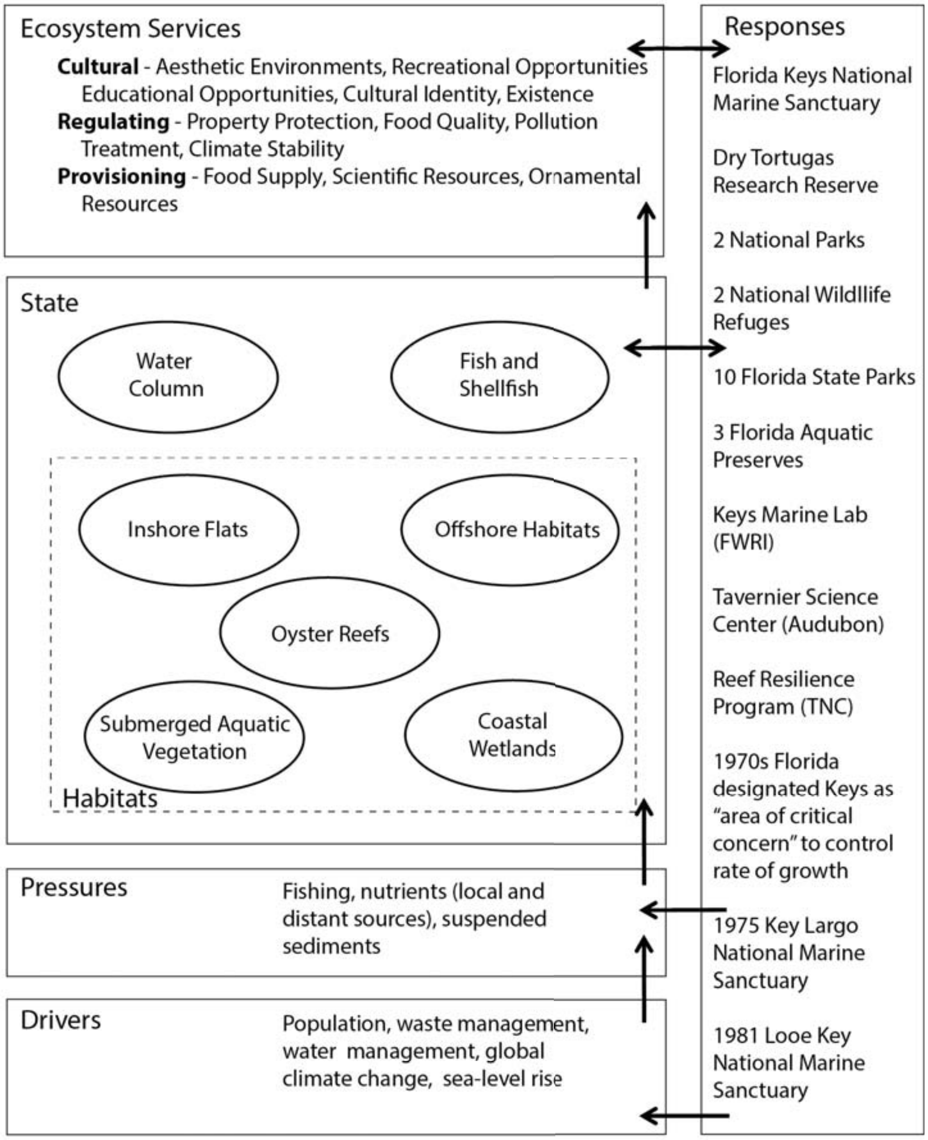


Figure 7. The Florida Keys/Dry Tortugas *State* model.

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

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)

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).

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

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)

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.

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,

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.

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 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.

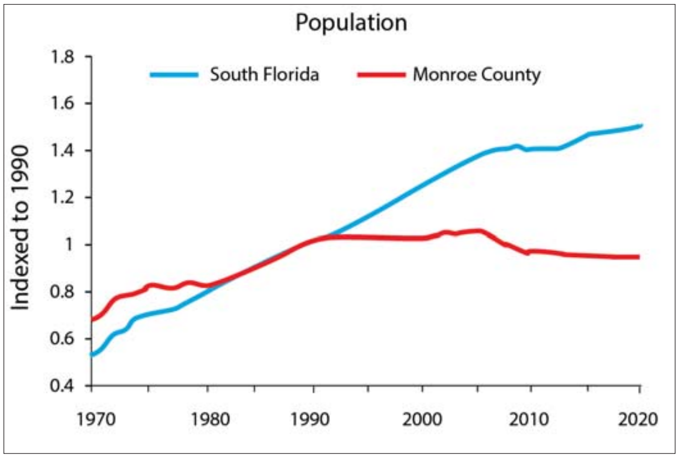


Figure 8. Human population in the Florida Keys, a local *Driver,* stopped its upward trend soon after 1990, even as the population in South Florida as a whole has continued to grow (Data sources: population http://edr.state.fl.us/population.htm).

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 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:

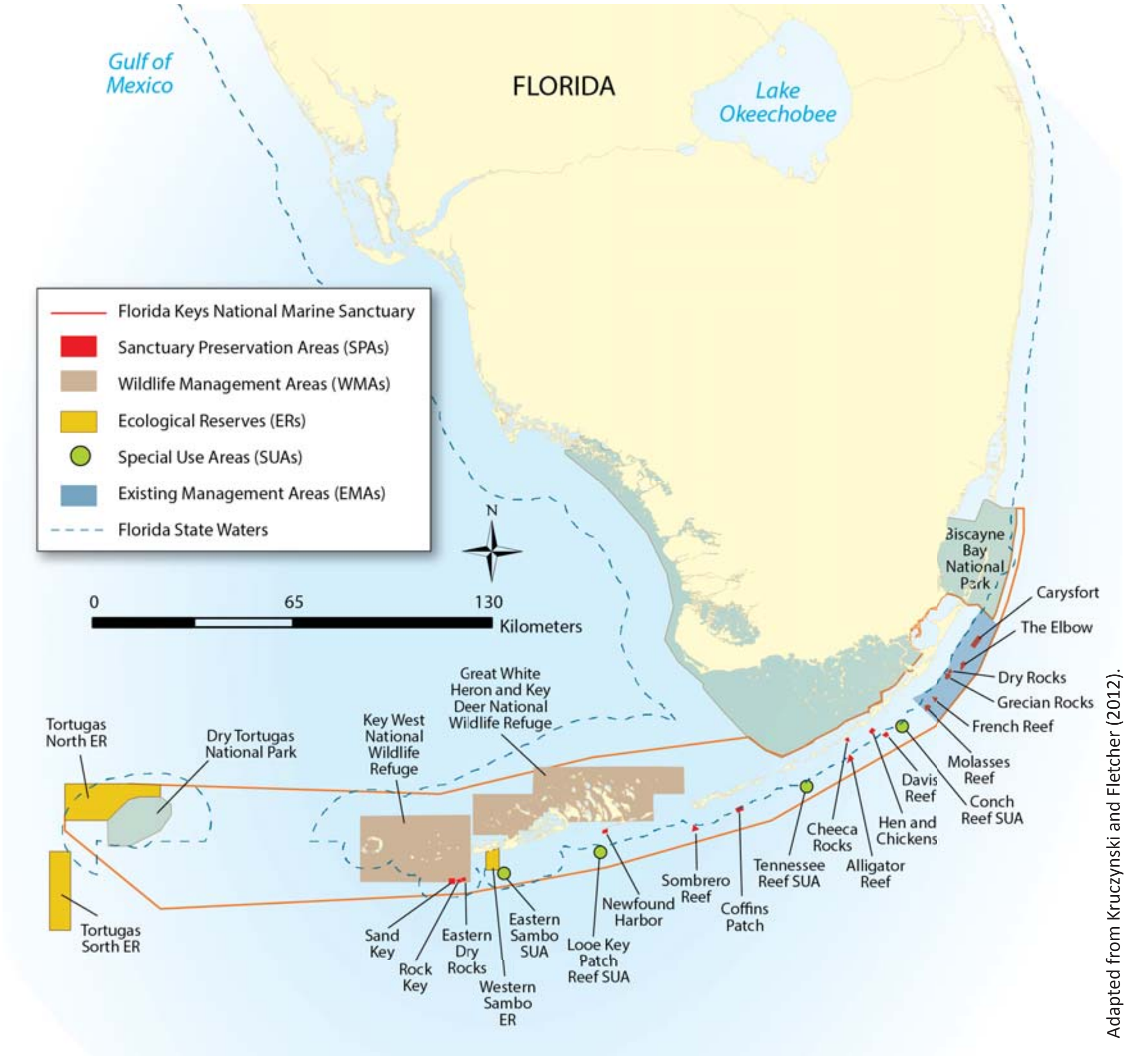
> *"To achieve the protection and preservation of living and other resources of the Florida Keys marine environment."*

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;
- 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."



Adapted from Kruczynski and Fletcher (2012).

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.

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 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.

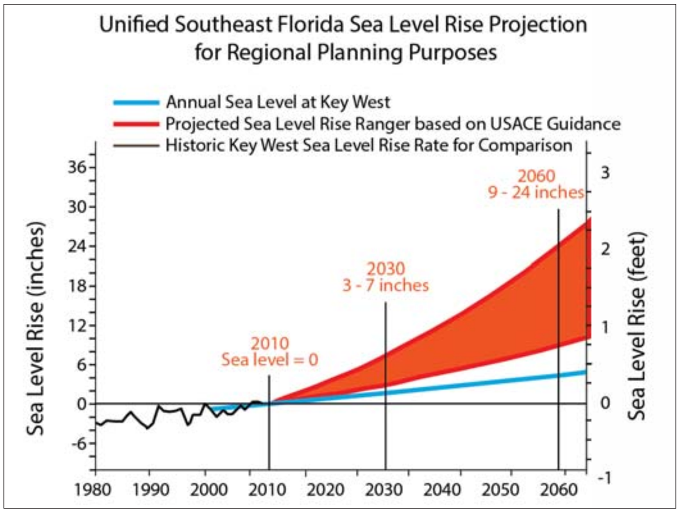


Figure 10. Unified southeast Florida sea-level rise projection for regional planning (Southeast Florida Regional Climate Change Compact, 2011; calculations courtesy of K. Esterson, U.S. Army Corps of Engineers).

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