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Integrated Conceptual Ecosystem Model Development for the Southwest Florida Shelf 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 "identify the defining characteristics and fundamental regulating processes of a South Florida coastal marine ecosystem that is both sustainable and capable of providing diverse ecosystem services." The approach taken in pursuing this goal is based on the hypothesis that scientists participating in a systematic process of reaching consensus can more directly and effectively contribute to critical decisions being made by policy makers and by natural resource and environmental management agencies. This report is an intermediate product of this consensus-building process.

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

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

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

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

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

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

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Acronyms

CERP	Comprehensive Everglades Restoration Plan
CHNEP	Charlotte Harbor National Estuary Program
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
NPS	National Park Service
NSP	Neurotoxic shellfish poisoning
QEI	Quantitative Ecosystem Indicator
RNA	Research Natural Area
SAV	Submerged aquatic vegetation
SEFC	Southeast Florida Coast
SFCME	South Florida coastal marine ecosystem
SWFS	Southwest Florida Shelf
SWIM	Surface Water Improvement and Management

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 second subregion to be addressed by MARES, the Southwest Florida Shelf (SWFS). What follows with regard to the SWFS is the input received from more than 60 scientists, agency resource managers, and representatives of environmental organizations beginning with a workshop held August 19-20, 2010 at Florida Gulf Coast University in Fort Myers, 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 second report of the MARES project, documents the development of a conceptual ecosystem model for the coastal marine waters surrounding the Southwest Florida Shelf (SWFS). 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.

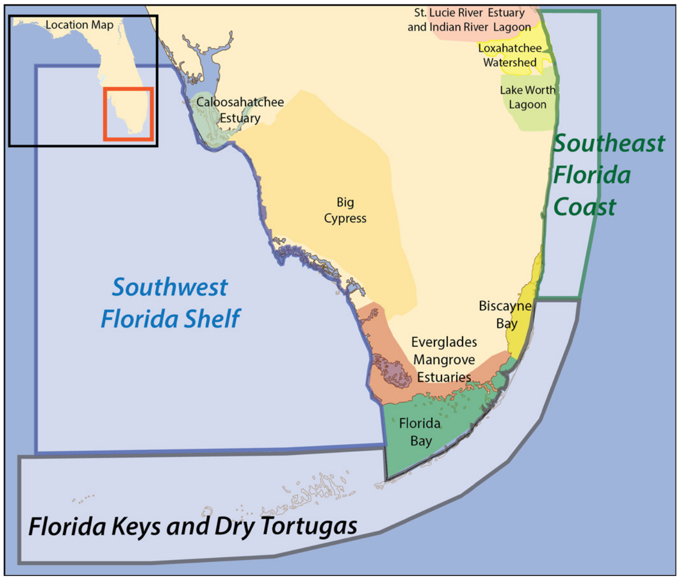


Figure 1. Map of the South Florida coastal marine ecosystem and three MARES subregions.

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

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

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

Oceanographic Processes Connect Subregions

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

Adapted from Kruczynski and Fletcher (2012).

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

diversity, and abundance of South Florida's valuable coastal 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 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

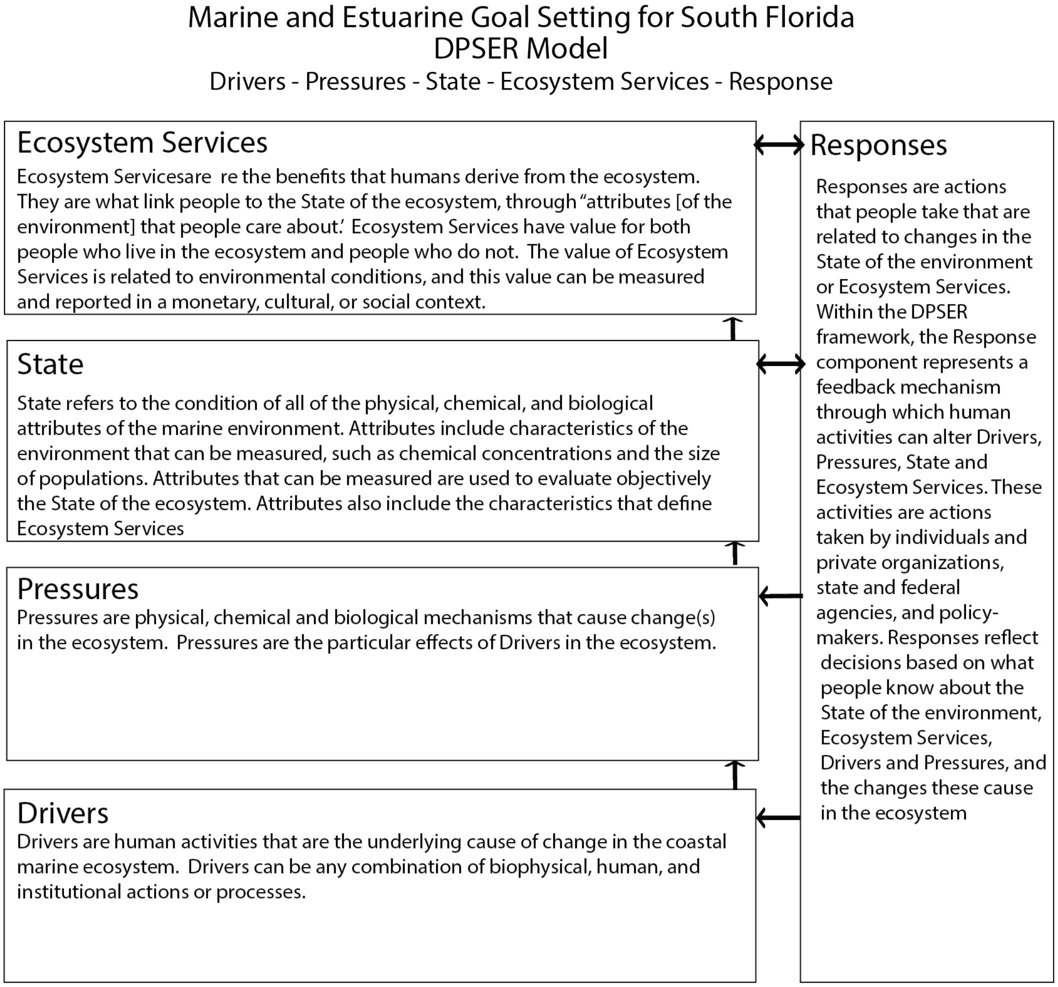
MARES relies upon a specific conceptual framework derived from the economic *Driver-Pressures-State-Impacts-Responses* (DPSIR) model (Tscherning *et al.,* 2012; OECD, 1993). While DPSIR has been used to inform environmental management (Mangi *et al.,* 2007), it does not explicitly incorporate the benefits 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 *Ecosystem Services* element (Figure 3).

Humans are integrated into every element of the DPSER framework, including the effects that people have on the environment and the values that motivate their actions to sustain the regional ecosystem. The first two elements of the model framework, *Drivers* and *Pressures*, describe factors that cause change in the condition of the SWFS 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 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).



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

Ecosystem Services

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

State

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

Pressures

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

Drivers

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

Responses

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

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

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 SWFS 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 Southwest Florida Shelf

Physical Setting: Dynamic Geomorphology

The southwest Florida coastal marine ecosystem lies along an expanse of low-lying coast that begins in Fort Myers and stretches south for about 125 miles (200 km) to Cape Sable, which marks the entrance to Florida Bay. Shallow coastal waters extend west for 150-180 miles (250-300 km) over the broad Florida Shelf. Geomorphic evolution of the southwest Florida coast and shelf is affected over the long term by relative rates of sea-level rise and sedimentation and over the short term by the prevailing sedimentologic processes and patterns of watershed hydrology. The present geomorphology reflects a north-to-south variation in the short-term factors during a period of relatively stable, slow sea-level rise. Four discrete geomorphologic provinces can be recognized along this section of coast. These are, from north to south: (1) Barrier Islands Province; (2) Ten Thousand Islands Province; (3) Everglades Province; and (4) Cape Sable Province (Figure 4).

The Barrier Islands Province extends south to Cape Romano, just south of Marco Island, where the longshore drift, which

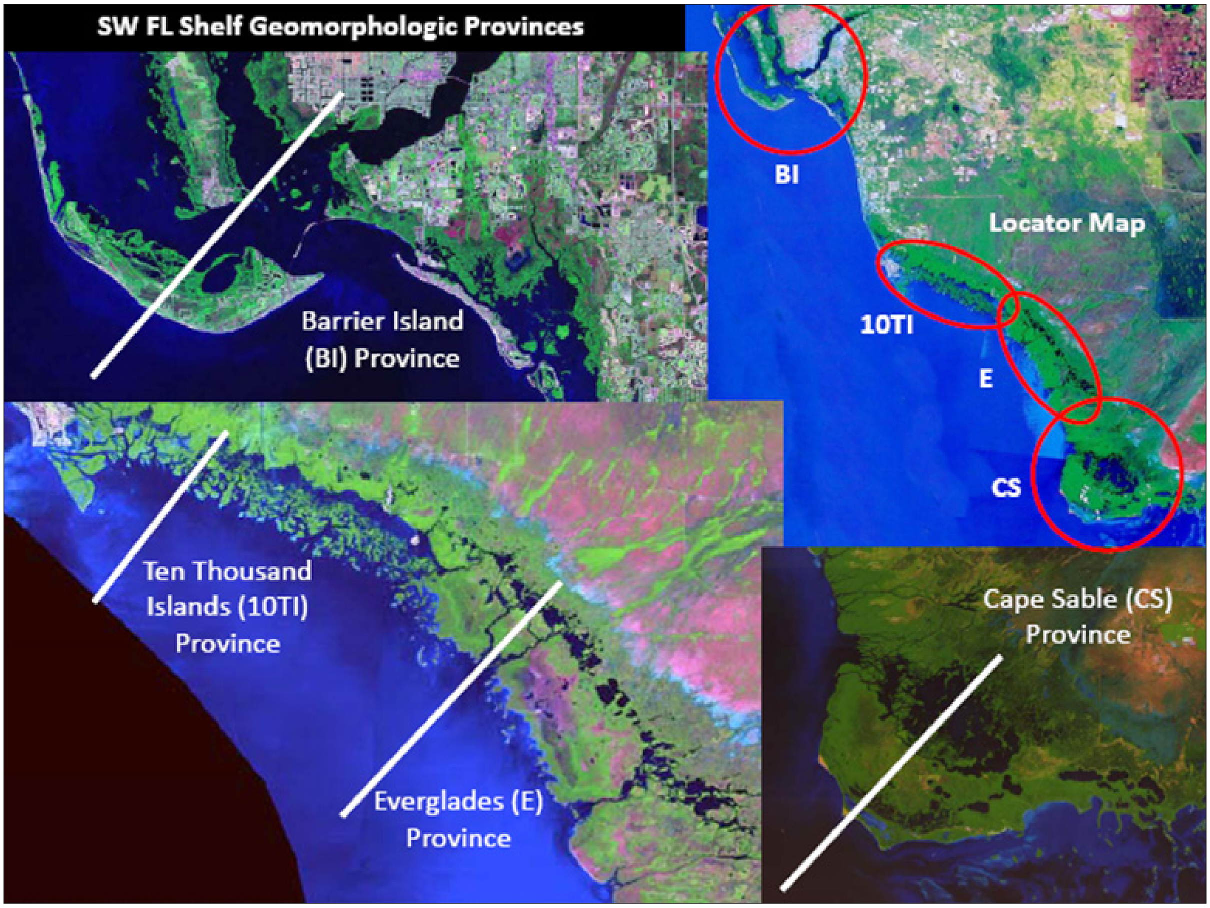


Figure 4. Four geomorphologic provinces of the Southwest Florida Shelf region: (1) Barrier Islands Province (upper left); (2) Ten Thousand Islands Province (lower left); (3) Everglades Province (lower left); and (4) Cape Sable Province (lower right).

carries quartz-dominated sand southward, separates from the shore. Shoreface sediments in this province are a mix of quartz sands and carbonate shell gravel; shell gravels become progressively richer relative to quartz sands toward the south or down-drift direction as longshore sediment supplies wane (Scholl, 1963). Environments associated with barrier islands include back-barrier mangrove forests and, occasionally, salt marshes, tidal flats, and flood tidal deltas landward of between-barrier inlets. The inner shelf's energy is focused on the seaward side of the barrier islands to create wave-influenced beaches and bars. Barrier islands serve to increase the residence time of freshwater in the back-barrier bays and wetlands and, by reducing wave and storm energy in their lee, create a suite of back-barrier environments not otherwise realized in an open coastal setting.

Coastal geomorphology of the Ten Thousand Island Province is a product of oyster reef development. These mangrove-forested islands assume a thin, irregular, anastomosing geometry because they mimic the shape of the precursor oyster reefs upon which they are established. These islands are a product of the last 3200 years of late Holocene history when sea-level rise was less than 10 cm per century (Wanless *et al.*, 1994). These islands have caused the coast to prograde through this 3200-year history. The islands located more seaward (i.e., outer islands) are older and, consequently, more robust than those located closer to the inner bay margins (Parkinson, 1989). The existence of these islands serves to trap freshwater in a fashion similar to barrier islands, and a productive estuarine environment thrives landward of the Gullivan Bay margin. Current rates of sea-level rise average 34 cm per century globally (Church and White, 2006). Accelerated sea-level rise, however, will ultimately lead to Ten Thousand Island instability and eventual loss, creating a more open coast.

The Everglades Province begins abruptly just southeast of Everglades City. The geomorphology is characterized by numerous large islands separated from the mainland by inner bays. Several tidal rivers (e.g., Chatham, Lostman's, Harney, and Broad rivers) connect the inner bays to the coast. Hoye (2009) has demonstrated that the Everglades Province's inner bays are degradational features, formed through the loss and deflation of peatlands. This contrasts greatly with the origin of the Ten Thousand Islands' inner bays which are constructional, rather than degradational features. The structure of the Everglades Province generates a unique mosaic of habitats, compared with the Ten Thousand Islands Province. Tidal mixing with marine water in the inner bays is more restricted, and these bays receive greater volumes of freshwater from slough-way sheet flow. Oyster reefs are absent or rare within the inner bays, yet can be prolific on the outer coast adjacent to river mouths. Seaward of the outer margin, expansive mud and sand flats exist. These are attributed to storm ebb-flow deposition following hurricane passage (Perlmutter, 1982; Risi *et al*., 1995; Tedesco *et al*., 1995).

The southernmost geomorphic region is the Cape Sable Province. Overall, Cape Sable Province's origin is similar to the Everglades Province, but here wetland degradation inshore of the coastal margin has progressed further to generate the larger bays. Oyster reef to mangrove-island progradation is absent here; even the river mouths lack prolific oyster reef development, presumably due to the greater influx of freshwater. Whitewater and Oyster bays are the two largest features that define the inshore geomorphology. Whitewater Bay's scalloped perimeter suggests a wetland peat degradational origin similar to what has been proposed for the inner bays in the Everglades Province. The mosaic of habitats in the Cape Sable Province is similar to what is seen in the Everglades Province. The inner bays are more expansive and generally lack oyster reef development. A lagoon (i.e., marine waters trapped behind the coastal ridge) sits between the inner bay and the outer coastal margin.

Connectivity

Circulation patterns within South Florida coastal waters maintain the vitality and variety of the ecosystem, but they also provide a conduit for the input of pollutants from remote upstream regions (see Figure 2). The SWFS subregion includes the southern extreme of the West Florida Shelf as it merges with the Florida Keys. Thus, this region is highly influenced by the processes occurring on the West Florida Shelf, such as strong synoptic wind forcing, seasonal changes in wind forcing, Loop Current excursions into the northeast Gulf of Mexico, and river discharge and stratification. The importance of the connection between this region and remote sources of pollutants was reiterated during the Deepwater Horizon oil spill in 2010.

Recirculating current systems link the different subregions of the South Florida coastal ecosystem and form an effective retention zone for locally-spawned larvae. Retention in countercurrents and eddies provide the larval pathways and opportunities for recruitment from local, regional, and Gulf-wide sources. Trajectories of near-surface drifters deployed in the Shark River discharge plume show that there are three common pathways that connect the entire South Florida coastal system (Figure 5).

The two primary pathways are either to the southeast and through the passages of the Middle Keys, which is most common during winter and spring, or southwest to the Dry Tortugas, which is most common during the fall.

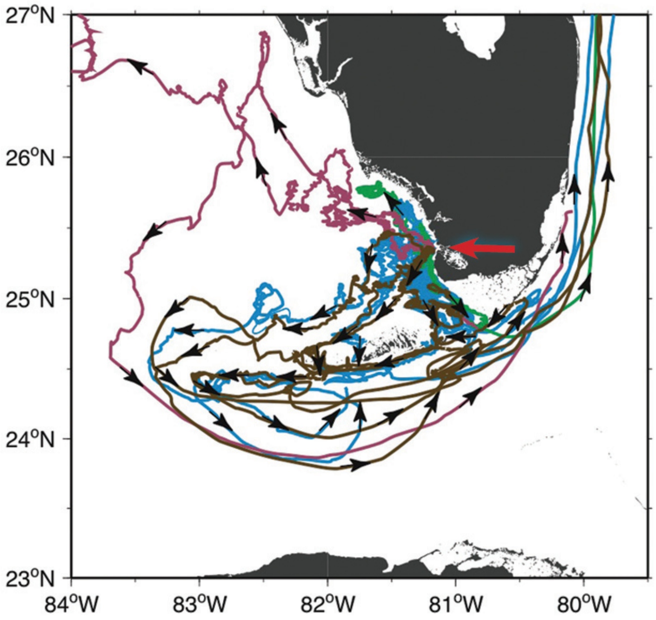


Figure 5. Circulation patterns link the Southwest Florida Shelf to local and regional waters. Shown here are the pathways of satellite-tracked surface drifters deployed in the Shark River discharge plume (red arrow) from September 1994-February 2000. The lines show seasonal pathways of flow: winter is blue; spring is green; summer is lavender; and fall is brown.

Advective time scales to reach the Keys coastal zone are one to two months for these routes. The third pathway is to the northwest in the summer and eventual entrainment by the Loop Current, followed by transport to the Dry Tortugas. This exchange route takes place over a three- to six-month time period. After drifters reach the Keys coastal zone, they tend to either recirculate in coastal eddies and wind-driven countercurrents for periods of one to three months, or become entrained in the Florida Current and removed from the coastal system.

The southeastward mean flow connecting the two shelf regions provides the source water for western Florida Bay and entrains the freshwater outflows from the Everglades and through the Ten Thousand Islands. The magnitude of this mean southeast flow is about 100-200 times larger than the freshwater outflow from the Everglades, which results in a low-salinity band that is trapped along the coast of the Ten Thousand Islands and extends to the southeast into western Florida Bay. Thus, the sustainability of ecosystems in South Florida waters is dependent on water management policies of the entire region, as well as those of upstream regions in the eastern Gulf of Mexico.

Low-salinity intrusions into South Florida coastal regions from southward transport down the SWFS and entrainment along the Florida Current front show the region to be significantly linked to remote regions of the eastern Gulf of Mexico. Although the physical mechanisms providing the linkages are not well understood, the most likely causes are the Loop Current and its influence on shelf circulation (Hetland *et al.*, 1999).

The variability of local circulation patterns is highly dependent on synoptic-scale winds. The strongest subtidal currents are in the alongshore (north-south) direction and are a direct barotropic response to alongshore winds. Seasonal changes in wind forcing also produce seasonal differences in the strength and variability of the currents, with greater current amplitudes in winter following cold front passages and weaker currents in summer. There is also a seasonal pattern in the upper layer currents which are more southward in the winter, spring, and fall, changing to northward in the summer with a shift of summer winds to the southeast. The lower layer currents are more persistent toward the south throughout the year.

Human Population

South Florida experienced a rapid change in economic and demographic factors within the last century. Florida was the only U.S. state 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 anticipated to have a population of 8.5 million, 2.4 million more than today (South Florida Economic Forecasting Partnership, 2006). The population size of South Florida influences many regional- and local-scale drivers like coastal development, agriculture, wastewater, fishing, and boating.

Human population and development along the SWFS coast is restricted to the the coastal zones of Collier and Lee counties, which are in the northern half of the subregion, i.e., in the area described previously as the Barrier Islands Province (Figure 6). Southwest Florida was sparsely populated until completion of the Tamiami Trail (U.S. Route 41) in 1928, which provided reliable road access from Tampa Bay to Miami. Retirement income is the single

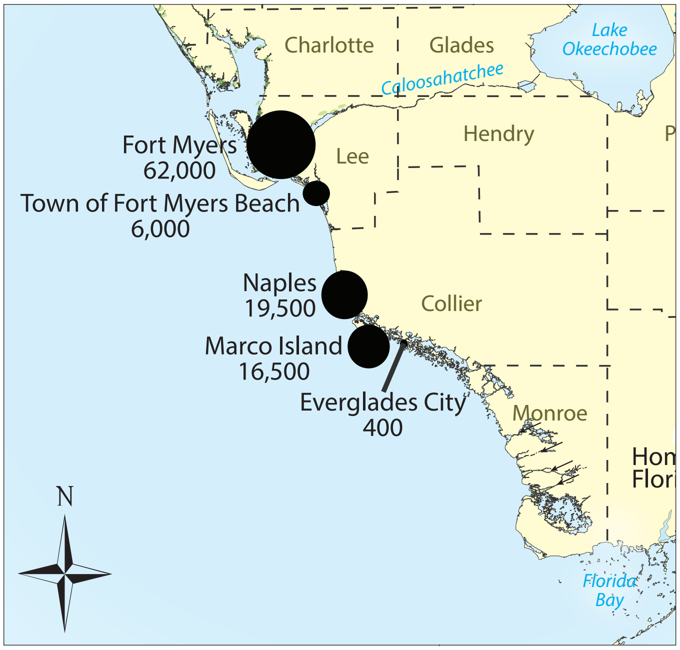


Figure 6. Population centers in southwest Florida (Bureau of Census, 2010).

largest component of the region's economic base. Tourism is the next largest component of the economy; the population increases by 30 percent during the winter. Agriculture is the third largest component of the economy. Until the recent economic downturn, this was one of the fastest growing areas in Florida.

Collier County

Collier County is on the southwest coast of Florida, bordering the Gulf of Mexico with Naples as its largest city. In 2010, the county had 321,520 residents. Eleven percent of county residents live in the three incorporated municipalities: Everglades City, Marco Island, and Naples. Over the last ten years, the population in this county grew by 28 percent. The University of Florida, Bureau of Economic Research projects the county's population will reach 330,700 by 2015.

Lee County

Lee County is on the southwest coast of Florida, bordering the Gulf of Mexico with Cape Coral as it largest city. In 2010, the county had 618,754 residents. Forty-four percent of county residents live in the five incorporated municipalities: Bonita Springs, Cape Coral, Fort Myers, Fort Myers Beach, and Sanibel. Over the last ten years, the population in this county grew by 40 percent. The University of Florida, Bureau of Economic Research projects the county's population will reach 625,500 by 2015.

The Southwest Florida Shelf Integrated Conceptual Ecosystem Model

Conceptual Diagram: Picturing the Ecosystem

The first step in the systematic MARES process is to develop conceptual diagrams (here a series of cross-section infographics) of the geographic provinces, the processes operating upon them, and the factors affecting their condition (Figures 7-10). The SWFS ecosystem consists of benthic offshore habitats, inshore flats, coastal wetlands, oyster reefs, and submerged aquatic vegetation (SAV), as well as the overlying water column and the fish and shellfish that move among these habitats (see appendices for more information). Degradation of habitats is a major concern in the SWFS because it reduces ecosystem services that

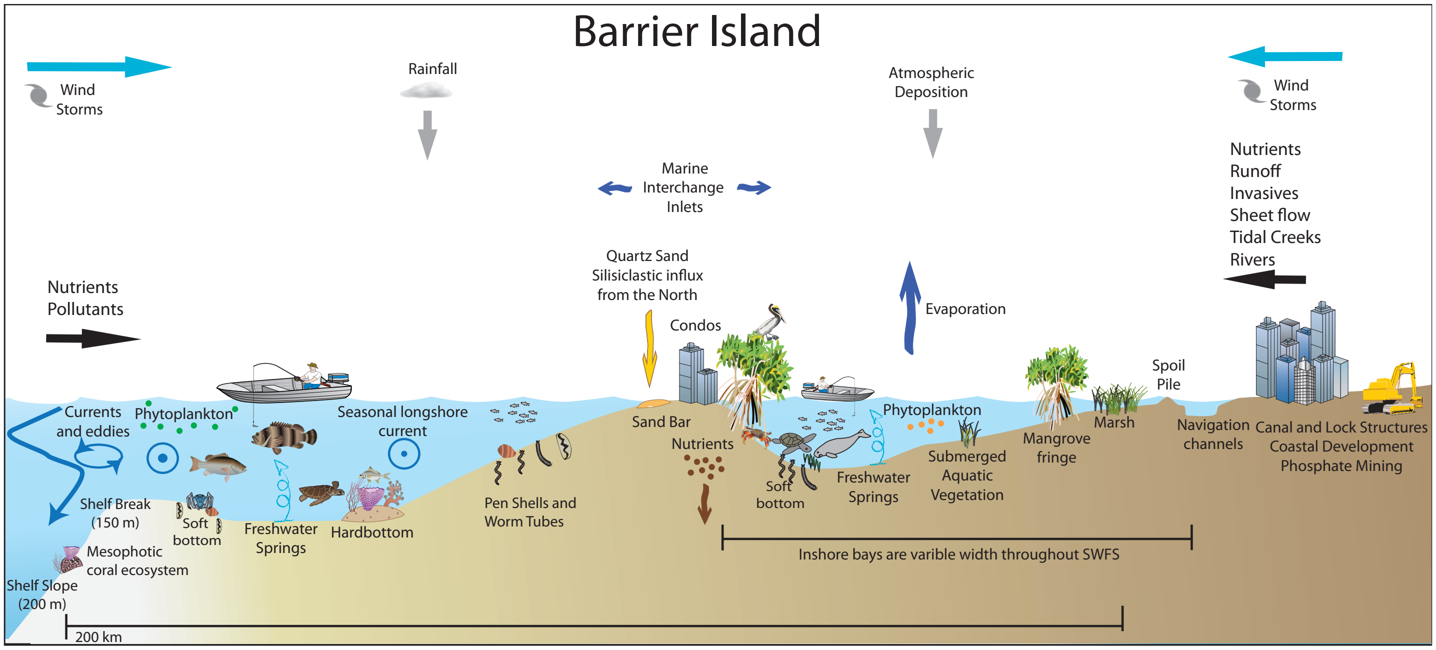


Figure 7. Conceptual diagram of the Southwest Florida Shelf Barrier Islands Province ecosystem, processes operating upon it, and factors affecting its condition.

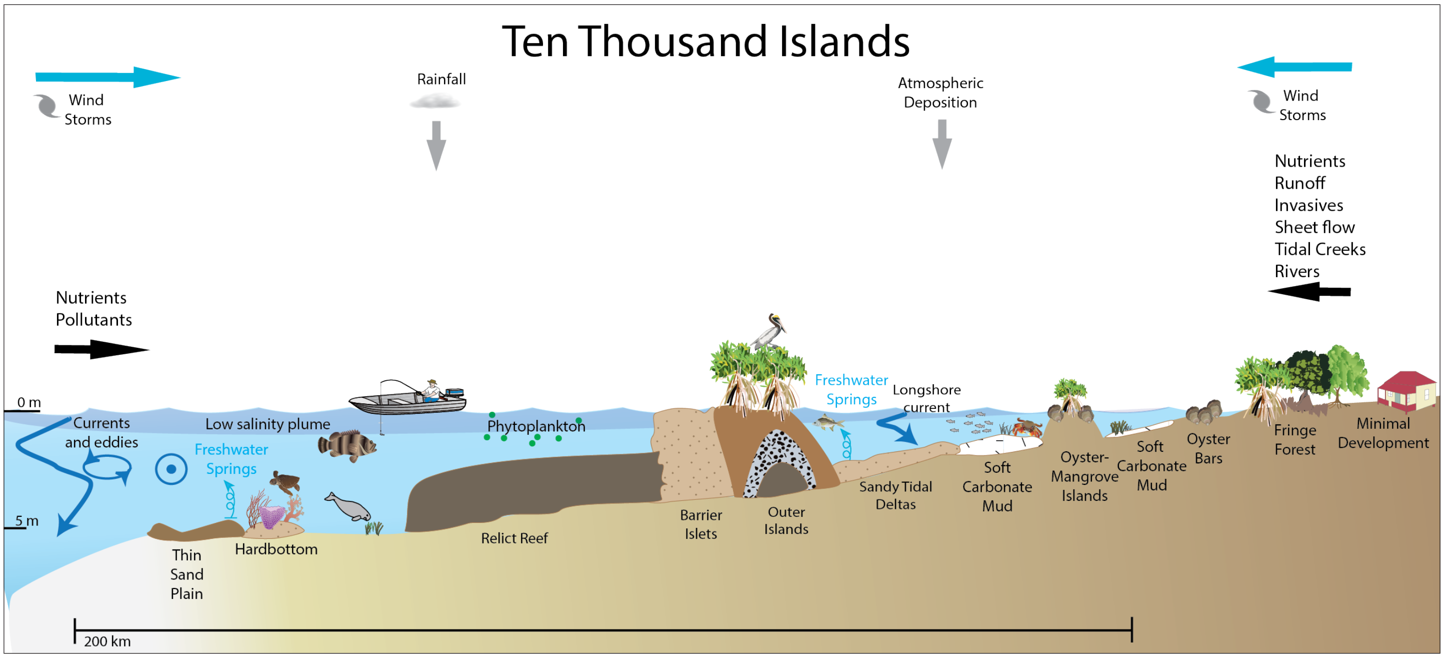


Figure 8. Conceptual diagram of the Southwest Florida Shelf Ten Thousand Islands Province ecosystem, processes operating upon it, and factors affecting its condition.

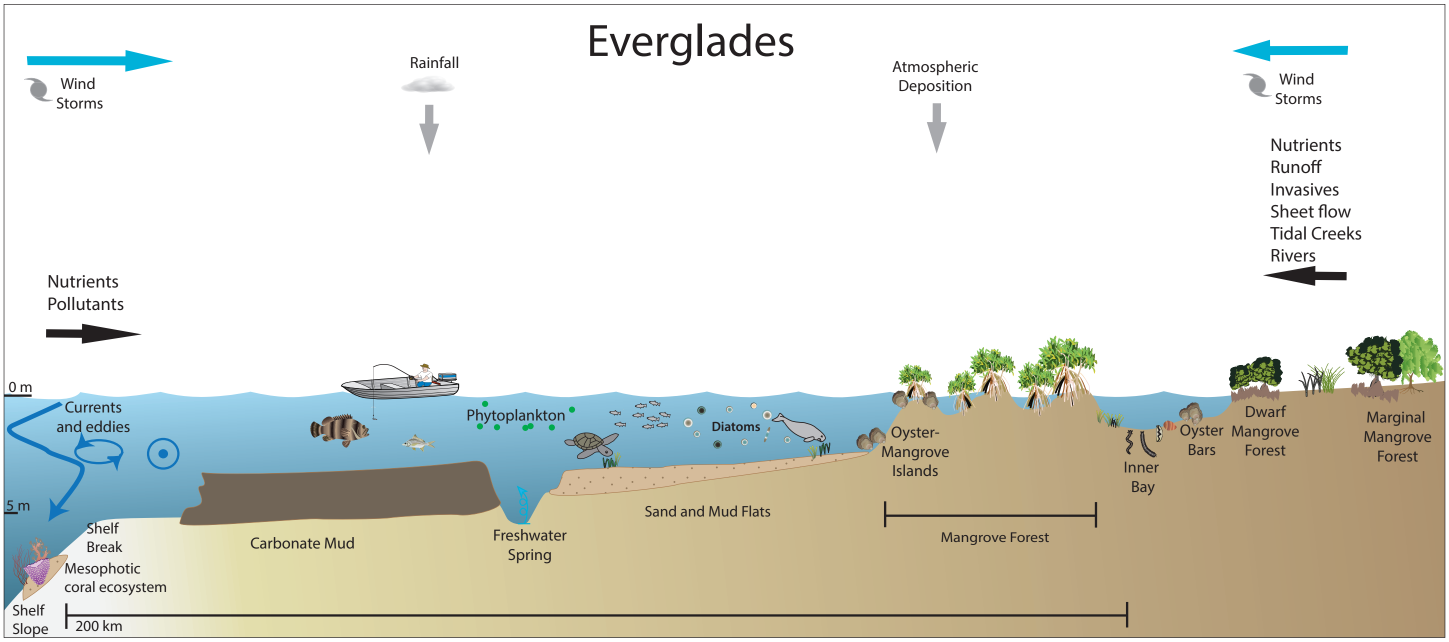


Figure 9. Conceptual diagram of the Southwest Florida Shelf Everglades Province ecosystem, processes operating upon it, and factors affecting its condition.

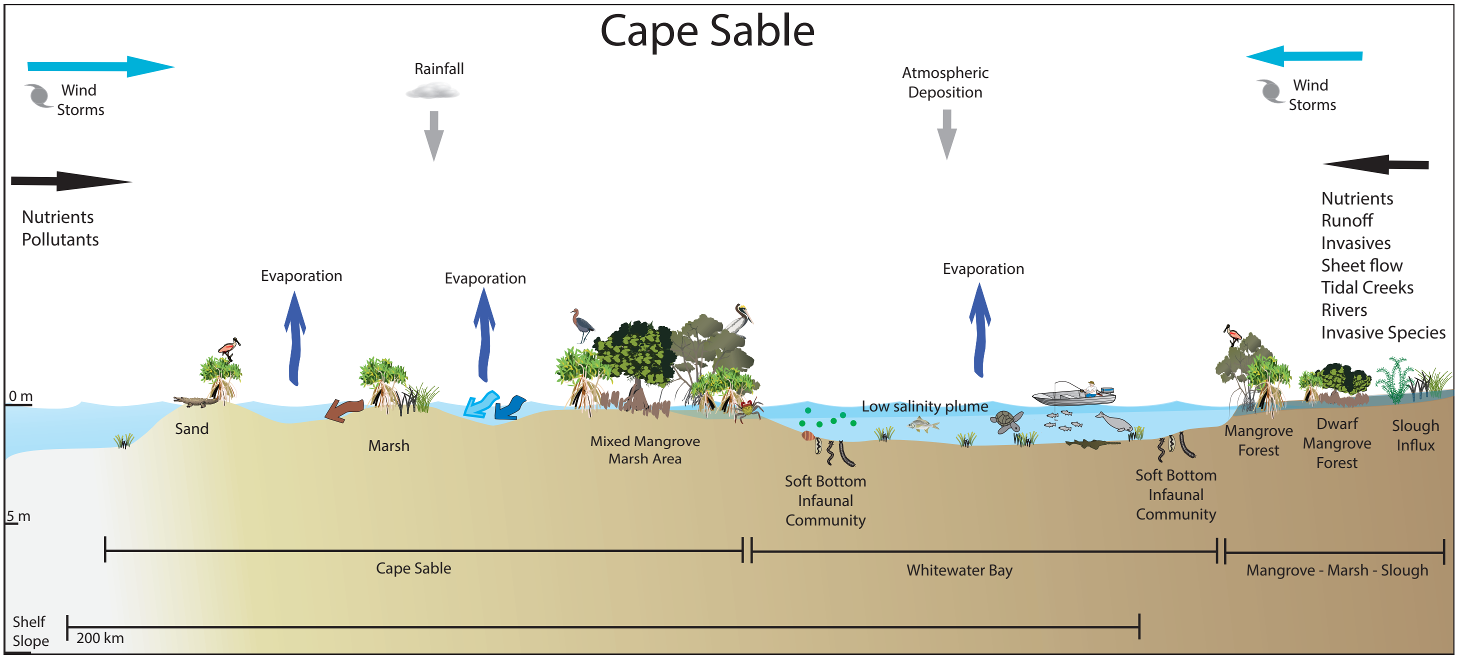


Figure 10. Conceptual diagram of the Southwest Florida Shelf Cape Sable Province ecosystem, processes operating upon it, and factors affecting its condition.

residents rely upon, including recreational and commercial fishing and tourism. Local factors that affect the ecosystem and its services are altered freshwater flows, fishing, 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 increasing water temperatures. Application of the DPSER framework leads to construction of narratives of the processes that sustain and change the ecosystem based on elements identified in the conceptual diagram (Figure 11).

Applying the Model in the Southwest Florida Shelf: Altered Freshwater Inflows

To illustrate how elements of the MARES DPSER model can be used to organize and analyze an ecosystem management issue in the SWFS, consider the issue of altered freshwater inflows, which are the focus of a number of management activities. In this case, the *Drivers* of change in the coastal marine ecosystem are regional water management in South Florida and wetland drainage for housing development near the southwest coast. Major concerns related to regional water management focus on the use of the Caloosahatchee Estuary as an artificial outlet from Lake Okeechobee and the use of the lake as a reservoir for regional water supply. The effects of local development are illustrated by efforts to drain the now-defunct Golden Gates Estates development, which involved construction of the Faka-Union Canal (Figure 12). In both cases, the resulting changes to the quantity, quality, timing, and distribution of freshwater inflow represent the *Pressures* acting on the coastal marine ecosystem.

These *Pressures* cause a change in the *State* of the ecosystem, most directly on conditions in the water column. In both cases, the major effect of altered inflow has been to exacerbate extreme flows. Inflow to the Caloosahatchee Estuary fluctuates between extremely high flow and no flow. Construction of the Faka-Union Canal has had the effect of collecting and focusing freshwater inflow from wetland discharge in the vicinity of the canal outlet while reducing freshwater inflow in adjacent areas of the coast. Changes in freshwater inflow alter salinity patterns and the availability of nutrients, particularly in nearshore waters.

These changes, in turn, alter the distribution and quality of wetland and benthic habitats and the *Ecosystem Services* they provide. For example, both oyster reefs and SAV beds

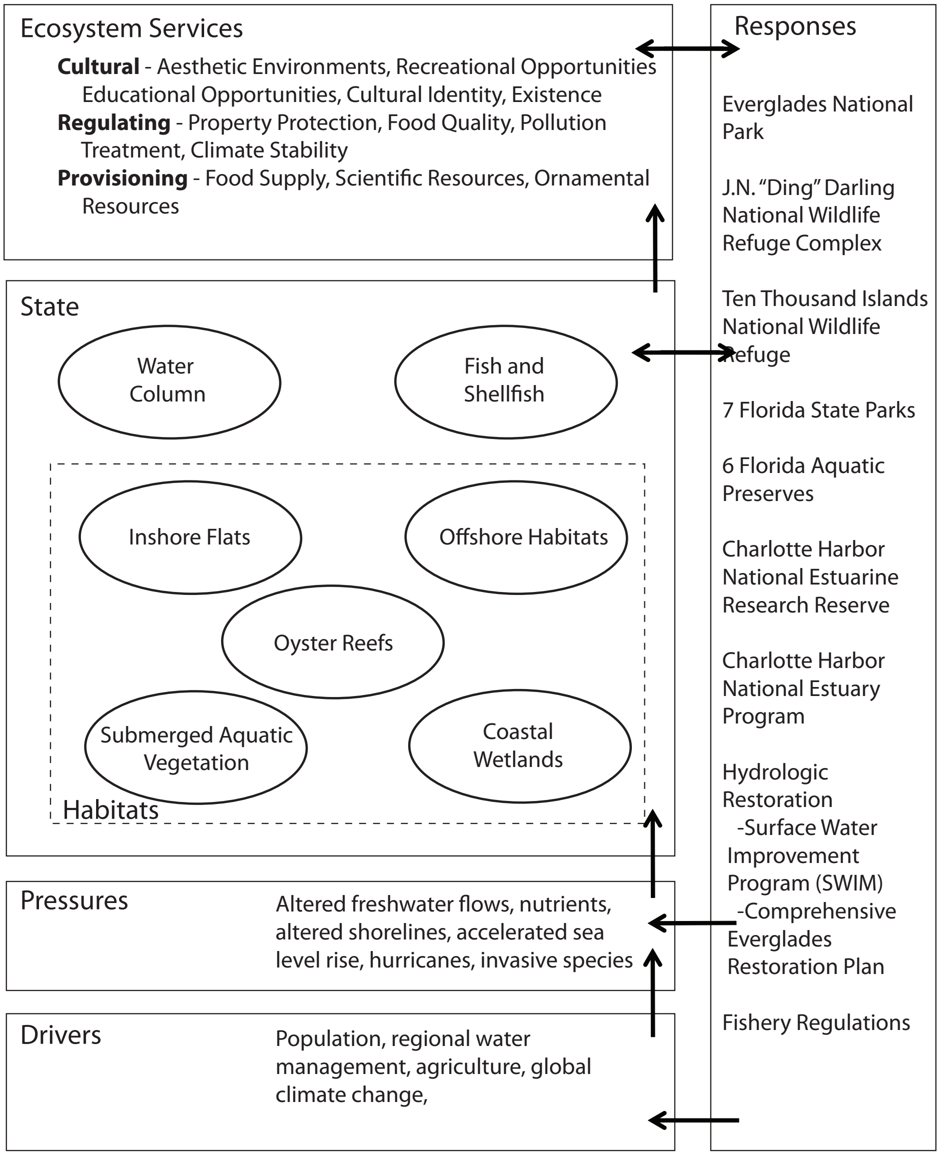


Figure 11. MARES Drivers-Pressures-Ecosystem Services-Response framework for the Southwest Florida Shelf subregion.

are sensitive to changes in salinity and nutrients in the water column, and both serve as nursery and feeding habitats that support commercial and recreational fisheries in the region. Freshwater discharge from Lake Okeechobee is a factor in the development of harmful algal blooms that directly affect people's enjoyment of coastal waters.

In *Response* to interest to maintain and improve these *Ecosystem Services*, water managers have initiated various efforts to mitigate the adverse effects of altered freshwater inflow. In the area of the Faka-Union Canal, there are efforts to restore more natural hydrologic conditions in the drained wetlands and redistribute flows to the coast. In the case of managing inflows into the Caloosahatchee Estuary, water managers must weigh the impacts and benefits in the coastal marine ecosystem against competing impacts and benefits in other parts of the South Florida region that are now also tied to Lake Okeechobee. Here, the management *Response* includes efforts to monitor changes in conditions in the estuary and coastal waters and better document and evaluate the impacts of changes in freshwater inflows.

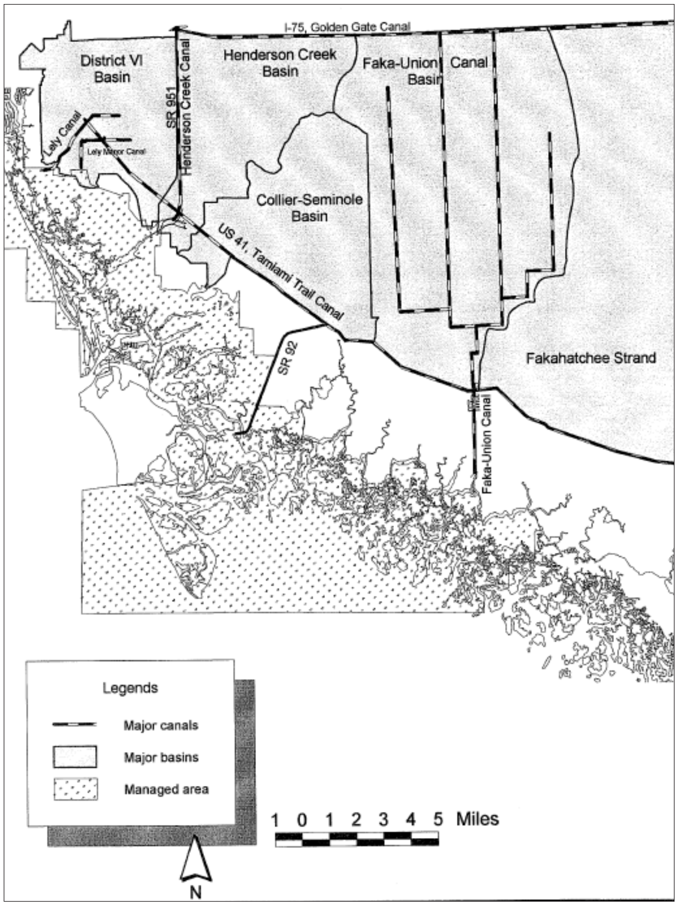


Figure 12. Canals affecting freshwater inflow into the Ten Thousand Island Province (from Rookery Bay management plan).

Drivers and Pressures: Sources of Change

It is useful to distinguish between *Pressures* arising from far-field causes and those arising from near-field causes. The distinction between far-field and near-field *Pressures* has practical implications in deciding how to respond to the resulting changes in the ecosystem. Far-field *Pressures* alter environmental conditions at the boundary of the ecosystem, and their effects propagate throughout the ecosystem. Far-field *Pressures* of concern in the SWFS region include pressures related to climate change and pollution from freshwater runoff into the Gulf of Mexico from distant sources like the Mississippi River. Near-field *Pressures* are generated internally, and their effect varies in intensity across the ecosystem. Near-field *Pressures* of concern include altered freshwater flows generated from within South Florida and nutrient runoff from agriculture and coastal communities in the region. Concern is growing over the impact of the lionfish, a recently arrived invasive species, on native fisheries.

Far-Field Drivers and Pressures: Global Climate Change

Although far-field factors are outside of the realm of management control within the SWFS, 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 SWFS 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 SWFS is climate change resulting from the rising concentration of CO_2 in the atmosphere. Long-term changes caused by ocean acidification, sea-level rise, sea surface temperature, rainfall, and hurricane severity and frequency are expected to occur as a result. South Florida, with its low elevation, high coastal population density, and unique ecosystems, including the Everglades and coastal wetlands, 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.

Ocean Acidification

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 concentration of CO_2 lowers 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 $HCO3^-$ (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.

Accelerated Sea-Level Rise

The SWFS is situated at a low elevation and is vulnerable to sea-level rise in the United States. The IPCC 2007 projections for sea-level rise range from 20-60 cm during the 21st century; however, these rates do not include factors such as ice sheet flow dynamics that could significantly increase the rate. The more recent *Copenhagen Report* (Allison *et al*., 2009) states that the IPCC (2007) report underestimated sea-level rise and that it may be as much as twice what has been projected. "For unmitigated emissions [sea-level rise] may well exceed 1 meter" by 2100, with an upper limit at approximately 2 meters (Allison *et al*., 2009).

The Southeast Florida Regional Climate Change Compact (2011) counties have developed a consensus trajectory for sea level through 2060 (Figure 13). The consensus sea level projections are 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. Sea level in South Florida is projected to rise one foot above the 2010 reference level, relative to land surface, sometime between 2040 and 2070. A two-foot

Table 1. Far-field drivers and pressures of greatest importance to the Southwest Florida Shelf.

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)

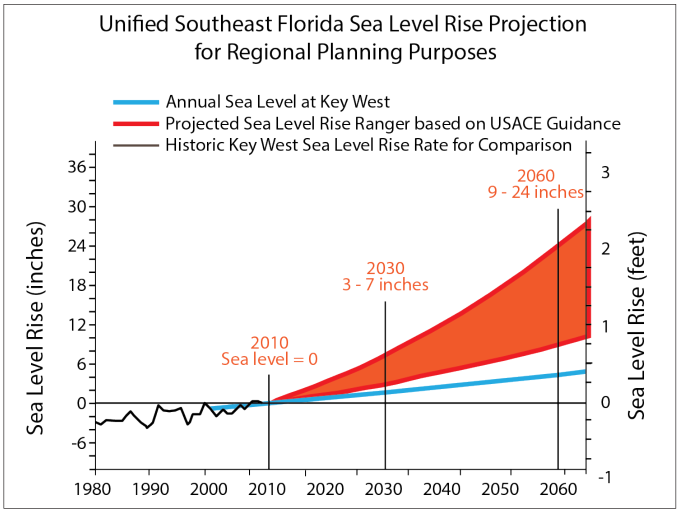


Figure 13. Unified southeast Florida sea-level rise projection for regional planning (Southeast Florida Regional Climate Change Compact, 2011; calculations courtesy of K. Esterson, U.S. Army Corps of Engineers).

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. Sea level rose at an average rate of 0.88 inches per decade between 1913 and 1999.

The global phenomenon of climate change and sea-level rise will alter the relative position of sea level, tides, and currents along the SWFS. The geomorphology of the extensive shallow water, including numerous mangrove islands, 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, 2000). 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 the coastal systems, including increased erosion and saltwater encroachment. Continuation of this rate will push marine water far 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 SWFS is that this will also push storm surge from storms further inshore.

Unless matched by a compensating increase in sediment accretion, the acceleration of sea-level rise will alter the balance between these two processes that has prevailed in recent times. The result will be potentially rapid changes in the geomorphology of the coast. Over decadal and centennial time scales, a high rate of sea level rise increases the tidal prism. Intertidal flats may become subtidal; subtidal flats may deepen and experience lower ambient light levels and greater frequencies or intensities of hypoxia. With deepening comes a concomitant change in sedimentary character, with substrates becoming finer grained and more mud rich. Oyster reefs become less productive with increasing subtidal depth and can effectively “drown” and disappear; such phenomena have been documented in Holocene sediment cores. Mangrove-forested islands can also drown when the rate of the sea-level rise exceeds the rate of peat production.

Accelerated sea-level rise and the resulting change in shoreline morphology also affects the distribution of salinities within the estuaries and, therefore, the position of the salinity gradient and ecotones. Shifts in salinity affect an organism’s ability to osmoregulate and can cause physiologic stress and mortality. Changes in the salinity gradient not only shift the biogeographic distribution of organisms, but may also place appropriate salinities in what is otherwise a less hospitable habitat due to other environmental conditions. For example, the incursion of higher salinity water within estuaries of the Ten Thousand Islands has placed the most productive waters for oyster growth and reproduction within the river channels, rather than the inner bays. River channels have much less accommodation space for oyster reef development than inner bays, and river channel substrates are generally too mobile to permit oyster settlement and survival.

Increasing Temperature

Climate forecasts predict an increase in summer air temperatures of between 2-4°C and an increase in winter air temperatures by 3°C 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 SWFS.

Altered Rainfall and Evaporation

The net effect that global climate change will have on rainfall and evaporation in South Florida is uncertain. The IPCC (2007) report indicates that there will be a likely decrease in precipitation over subtropical land regions and increased evaporation rates (Allison *et al.*, 2009). However, increased temperatures are also associated with an increase in the frequency of thunderstorms, particularly in the tropics and southeastern United States (Trap *et al.*, 2007; Aumann *et al.*, 2008). Thunderstorms are the major source of rainfall during the summer wet season in South Florida. In addition to rainfall, thunderstorms play a role in fire generation in south Florida (Gunderson and Synder, 1994).

Frequency and Intensity of Tropical Storms

The IPCC Summary Report for Policymakers (2007, p. 12) states that "it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and heavier precipitation associated with ongoing increases of tropical SSTs" [sea surface temperatures]. The Copenhagen Report (Allison *et al.*, 2009) discusses evidence that hurricane activity has increased over the past decade, and the number of number of category 4 and 5 hurricanes has also increased globally. An increase in tropical storms promises increased rainfall over land and increased mixing of shallow surface waters of the Florida Shelf during the passage of these storms (e.g., Ortner *et al.*, 1984). The passage of intense storms can resuspend sediments and reduce the transparency of the water column (e.g., Chen *et al.*, 2009), resulting in a potential reduction in pelagic primary production in coastal waters. The combination of wind and storm surges have caused substantial die-off in the mangrove forests of the southwest coast (Smith *et al.*, 1994, 2009; Wanless *et al.*, 1994) with a number of related effects including increased erosion due to an uprooting of trees, increases in carbon and nutrients released into the waters, and repopulation of denuded areas by invasive species.

Near-Field Drivers and Pressures

Near-field *Drivers* and *Pressures* relate to the high rate of population growth and development occurring in Collier and Lee counties, which affect the coastal marine ecosystem directly through changes to the shoreline and indirectly through degradation of water quality and altered freshwater inflows (Charlotte Harbor National Estuary Program, 2008), Table 2. Water quality is affected by nutrient loads and

Table 2. Near-field drivers and pressures of greatest importance to the Southwest Florida Shelf.

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)

pollutants carried in runoff from developed and agricultural areas, in discharge from septic tanks and waste treatment plants, and deposition from the atmosphere. Development alters the hydrological functioning of wetlands locally, and water management for the South Florida region has altered the flow regime of rivers in the region. These hydrologic changes alter the amount, timing, and location of freshwater inflow to estuaries and inshore areas of the coastal marine ecosystem. This, in turn, affects the salinity of inshore waters and the many species of plants and animals that are sensitive to salinity.

Nutrients

Eutrophication of coastal waters, resulting from increased nutrient loads, can increase the occurrence of harmful algal blooms. The link between coastal eutrophication and harmful algal blooms has not been made definitively for the SWFS region (Walsh *et al.*, 2009; Vargo, 2009); however, eutrophication has been demonstrated to enhance the development of harmful algal blooms in other regions (cf., Anderson *et al.,* 2008).

Several sources contribute nutrients to the water column of the SWFS, including nutrient loading from freshwater inflows, nutrients released from benthic communities, and the intrusion of bottom waters from the Gulf of Mexico Loop Current. Estuaries are a major source of nutrients, in both dissolved inorganic and organic forms, that support primary production near the shore (Vargo *et al.*, 2008). In particular, dissolved organic forms of nitrogen are the major form of this essential nutrient in the rivers that flow into the SWFS coastal waters (McPherson and Miller, 1990). Further offshore, nitrogen and phosphorus enter the shelf ecosystem from upwelling of subsurface waters in the Loop Current (Walsh *et al.*, 2006). Additional biological inputs occur from the nitrogen-fixing cyanobacteria *Trichodesmium* spp., which often blooms in summer in response to the seasonal input of iron from atmospheric dust transported westward from the Sahara (Walsh and Steidinger, 2001). When *Trichodesmium* spp. bloom, they release measurable quantities of dissolved organic nitrogen that subsequently supports primary production in the water column. Direct atmospheric inputs of nitrogen also occur through wet and dry deposition in the eastern Gulf of Mexico (Paerl *et al.*, 2002). In total, these sources can support dense algal blooms on the SWFS, although no individual nutrient source is apparently sufficient to maintain prolonged bloom events (Vargo *et al.*, 2008; Vargo, 2009).

Altered Freshwater Inflows

The balance between saltwater influx from the marine systems and freshwater flow from the terrestrial systems is what defines the transitions within any coastal wetland environment. Landscape alterations and water management practices that change natural flow patterns are one of the primary drivers in coastal ecosystems (Davis *et al.*, 2005; Sklar and Browder, 1998). Changes in flow cause a cascade of changes to other key physical components of the ecosystems, including water depth, salinity, nutrients, and dissolved oxygen, which cause changes in biological components such as productivity, community structure, and species composition (Sklar and Browder, 1998). Diverting or limiting water flow affects the sediments carried by the rivers, which affects the supply of raw materials needed to maintain or build up the coast, and the nutrients to promote plant growth, critical factors that enable the coastal wetlands to keep pace with rising sea levels (Sklar and Browder, 1998). Altered freshwater flow patterns also have damaging consequences for eastern oysters (*Crassostrea virginica*) and, therefore, the entire oyster reef ecosystem (Volety *et al.*, 2009).

Freshwater is over discharged into some estuaries (e.g., Faka Union Bay in the Ten Thousand Islands and the Caloosahatchee River in the Barrier Islands Province), and the magnitude of freshwater releases can be extreme, causing freshets that can unduly stress faunas and floras. In other estuaries, freshwater sheetflow is interrupted because of drainage canal networks that redirect freshwater to one bay. This phenomenon has been particularly devastating to the bays west of Faka Union Bay in the Ten Thousand Islands which, as a result, have anomalously high salinities. The timing of freshwater delivery is also of importance. Freshets during times of spawning or larval recruitment can obviate an entire year's reproductive effort.

Freshwater inflows to the Caloosahatchee Estuary have been modified by construction of an artificial outlet from Lake Okeechobee into the Caloosahatchee River. Freshwater diversion into the Caloosahatchee Estuary is controlled by the Franklin Lock and Dam (S-79). The flow of water from the lake into the river is managed as part of efforts to control water levels in the lake. Freshwater release can be of great magnitude and result in dramatic fluctuations between near-marine salinity and freshwater. At low flow times, a salinity wedge threatens the upper limits of tolerance of the tape grass (*Vallisneria americana)* communities found in the upper Caloosahatchee Estuary. At the other extreme, dramatic freshwater discharge can lower salinities in San Carlos Bay to levels deleterious to seagrasses. Natural cycles of precipitation and the resulting increases and decreases in salinity do not always follow wet season (June through October) and dry season patterns (November through May) in the river downstream from the dam (Kraemer *et al*., 1999).

The quantity, timing, and distribution of freshwater inflow to Faka Union Bay and adjacent areas of the Ten Thousand Islands changed substantially with construction of a system of canals to drain the Golden Gate Estates development (Figure 12). Originally, the bay received freshwater inflow from the Wood River, a small natural tributary of Picayune Strand. The Faka Union Canal watershed now includes Southern Golden Gate Estates (SGGE, site of the present Picayune Strand Restoration Project, located between U.S. Highway 75 and State Road 41) and part of Northern Golden Gate Estates (NGGE), which lies north of U.S.Highway 75.

Popowski *et al*. (2004) provides the following summary of the resulting changes. Faka Union Canal discharge records measured at the gauging station located upstream from the outfall weir are available starting in 1969. The average discharges for the period of record are 115 cubic feet per second (cfs) during the dry season (November through May) and 460 cfs during the wet season (June through October) (SFWMD, 1996). An extreme discharge of 3,200 cfs occurred right after the canals were built. Flows exceeding 2000 cfs have occurred in recent years (i.e., 1995 and 1999) (District DBHydro database).

The canal system greatly increases the inflow of freshwater into Faka Union Bay at the expense of inflow to other nearby areas. Inflows are increased during the wet season and decreased during the dry. As a result, the transition between wet season flow and dry season flow has become more abrupt, and the natural seasonal difference flows accentuated. The canal system diverted surface and groundwater flow from Fakahatchee Bay, which lies directly east of Faka Union Bay and downstream from Fakahatchee Strand. The diversion reduced both wet season and dry season flows to the larger bay, although Fakahatchee Bay was influenced by low-salinity water entering from Faka Union Bay through a direct connection between the two bays. The canal system and associated road system also diverted surface and groundwater away from the small rivers and bays immediately west of Faka Union Bay, including Pumpkin River and Pumpkin Bay. Both spatial and temporal changes in salinity patterns occurred as a result of changes in freshwater inflow regimes (Popowski *et al*., 2004).

In the southwest coastal area of the Everglades, the altered freshwater regime has altered the hydroperiods and delivers relatively high nitrogen loads, stimulating productivity and leading to the invasion of opportunistic native plants and invasive exotics (Sklar and Browder, 1998). Childers *et al*. (2006) found that reduced freshwater flow was associated with higher total phosphorus from marine sources in the Shark River Slough mangrove estuaries. The volume of flow is also critical to productivity. There is an optimum flow level, below which nutrient deficiencies and soil oxidation can occur and above which abrasive flows and waterlogging of the wetlands can occur (Sklar and Browder, 1998).

Other Pressures: Invasive Species Introduction

The animal trade industry has resulted in the release of numerous non-native species to South Florida, including the marine ecosystem of the Florida Keys. One example is the spread of lionfish, *Pterois volitans*, that now inhabit the Bahamas and the east coast of the United States, including the Florida Keys National Marine Sanctuary (Whitfield *et al*., 2002, 2007). These predatory fish have been reported to kill 1.44 native fish per hour on average in nearby Bahamian coral reefs (Cote and Maljkovic, 2010). In fact, this high predation rate has resulted in a reduction of native fish recruitment by an average of 79 percent in reefs with *P. volitans* (Albins and Hixon, 2008).

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, which can be divided into five components to better describe its defining attributes and underlying processes: (1) water column; (2) fish and shellfish; and five habitat communities: (3) inshore flats; (4) submerged aquatic vegetation; (5) oyster reefs; (6) benthic offshore; and (7) coastal wetlands. *State* submodels for each are provided as appendices to this report.

Water Column

The water column encompasses the physical, chemical, and biological characteristics of the water column, including benthic sediment, phytoplankton, and zooplankton suspended in the water column. Water quality on the SWFS is affected by the biogeochemical processes that regulate the cycling and concentration of particulate and dissolved materials in the water column. A diverse set of sources and sinks for these constituents occur at the boundaries of the shelf waters and include bottom sediments, the contiguous oceanic waters of the Gulf of Mexico, and the riverine inflows along the west Florida coast. The spatial gradients in dissolved and particulate matter are mainly from higher levels at the coast to lower levels in offshore waters, with maximum concentrations of dissolved and particulate materials near the coastal inflows and estuaries. The constituents are modified through biogeochemical cycling in both the water column and the sediments. Residence times of dissolved and particulate matter on the Florida Shelf can be on the order of weeks to months, as the flow regime constrains surface waters onshore of a convergent boundary at mid-shelf (Yang *et al.*, 1999). Thus, two of the ecosystem attributes that people care about, harmful algal blooms dominated by the toxic dinoflagellate *Karenia brevis* (Steidinger *et al.*, 1998) and “blackwater” events (Hu *et al.*, 2003), can be retained on the inner shelf for periods of weeks to months.

Fish and Shellfish

The fish and macroinvertebrate fauna of the Ten Thousand Islands support both recreational and commercial fishing. The short list of target species inshore includes snook, tarpon, red drum, spotted seatrout, pompano, and sharks. Offshore, the principal target species are snapper, grouper, cobia, permit, barracuda, king and Spanish mackerels, and more sharks. Inshore are many other fish that provide good opportunities for anglers, as well as a myriad of smaller fish that serve as bait for fishermen and the prey of fishing targets. The first category includes spotted and sand seatrout, sheepshead porgy, and hardhead catfish. Browder *et al.* (1986) documented at least 79 fish species and 70 macroinvertebrate species that fit the lower and middle levels of the faunal food web. Dominant fish were bay anchovy, yellowfin menhaden, scaled sardine, striped anchovy, pinfish, and silver perch. Shirley *et al.* (2005) listed as dominants spotfin mojarra, silver jenny, fringed flounder, pigfish, and blackcheeked tonguefish. Pink shrimp were among the numerically dominant species in Shirley *et al.* (2005), and the total catch of pink shrimp was of similar magnitude in a 1972 trawl study of Fakahatchee and Faka Union bays by Carter *et al.* (1973). Pink shrimp were the second most abundant decapod, following caridean shrimp in abundance, in Browder *et al.* (1986). Species composition changes seasonally and varies by bay system (Shirley *et al.*, 2005).

Several species of special concern are a part of the aquatic fauna of the Ten Thousand Islands. Southwest Florida is the last stronghold for the endangered smalltooth sawfish, and 619,013 acres of the combined Ten Thousand Islands and Everglades regions have been declared critical habitat for this species. Waters of the Ten Thousand Islands are also important habitat for the goliath grouper, once an important fishery species. The West Indian manatee is another major endangered species living in the Ten Thousand Islands. Kemp’s Ridley, green, leatherback, and Atlantic loggerhead sea turtles are other listed endangered species for which the Ten Thousand Islands are an important habitat.

Habitats

Inshore Flats

Inshore flats are defined as flat bottom, sub- or intertidal habitats that lack an epifaunal oyster or sea grass community and are located inside the outer coastal margin. The two most significant environmental characteristics that control the communities of infauna and epifauna on a flat are the height of the substrate relative to mean sea level and the sedimentary consistency of the substrate. The distinguishing characteristics of relative water depth with respect to mean sea level and the sedimentary substrate composition are used to define inshore flat habitat types: habitats may be subtidal or intertidal; subtidal substrates may be composed of sand and mud or mud; and intertidal substrates are composed of sand. Additionally, intertidal sand flats occur as one of two varieties that are distinguished by the relative stability and residence time of the sands. Storm tidal deltas form on the inside edges of the outer and inner bays landward of tidal inlets. During storm flood tides, sands are transported landward and deposited on these deltas (ebb flood deltas may also occur seaward, but tend to be ephemeral, as the sands deposited in these features are quickly remobilized and transported away; El-Ashry and Wanless, 1965). Consequently, storm tidal deltas remain stable between storm and extreme tidal events. Intertidal sand flats also occur as beach aprons on the bayside of islands. These structures are influenced by waves and by tidal cycle fluctuations.

Submerged Aquatic Vegetation (SAV)

SAV, for the purpose of this conceptual model, includes the vascular underwater plants that live in estuarine and nearshore coastal waters. SAV beds are primarily comprised of three seagrasses: turtle grass (*Thalassia testudinum*), manatee grass (*Syringodium filiforme*), and Cuban shoal grass (*Halodule wrightii*). Seagrass beds are extensive in the shallow Gulf waters south of Cape Romano. Marine seagrasses that occur in the Ten Thousand Islands include the three species already mentioned and two *Halophila* species, star grass (*H. engelmannii*) and paddle grass (*H. decipiens*). In areas of low salinity, such as near the mouth of freshwater rivers and creeks, widgeon grass (*Ruppia maritima*) can be found. *Ruppia* is generally found in waters of 25 ppt or less; however, it can tolerate a wide range of salinities from fresh to 32 ppt. As a result, the distribution and abundance of *Ruppia* can vary seasonally. Tape grass (*V. americana*) is the dominant SAV in the upper Caloosahatchee Estuary and occurs in well-defined beds in shallow water.

Oyster Reefs

Oysters, *Crassostrea virginica,* are natural components of estuaries along the eastern seaboard of the United States, as well as the estuaries in the Gulf of Mexico, and were once abundant in the estuaries of southwest and southeast Florida (RECOVER, 2007). Along the southwest Florida coast, oysters exist within the estuarine and coastal areas as extensive reefs or isolated clusters or are attached to prop roots of red mangroves, often extending out at the base of mangroves. Oyster reef development occurred along the southwest Florida coast over the last 3500 years, with reef development having a significant impact on coastal geomorphology. As reefs become emergent at low tide, they become the centers for red mangrove propagule settlement, and reefs transform into mangrove-forested islands. These islands entrap freshwater and predispose the region to estuarine conditions (Parkinson, 1989; Wohlpart, 2007). In the present day, oyster reefs are extensive along the Charlotte Harbor to the Ten Thousand Islands, with reef development decreasing southeast of Chatam River towards Everglades National Park (Savarese *et al.*, 2004; Volety *et al.*, 2009). In estuaries north of Lostman's and Broad rivers, oysters are also found on the prop-roots of red mangroves fringing the inner bays. In most of the estuaries, the extent of oyster reef coverage ranges between 5-20 acres (Volety and Savarese, 2001; Savarese *et al.*, 2004; Volety *et al.*, 2009).

Benthic Offshore

The "live bottom" and other benthic offshore habitats on the continental shelf support the biological diversity of the SWFS region, although the connectivity to inshore estuarine areas and to the Florida Keys is not well understood. Commercially valuable fish and invertebrate species (e.g., red drum, pink shrimp, stone crab) use the shelf and estuaries for part of their life cycle and depend on benthic habitats in the Gulf of Mexico. Benthic offshore habitats are thought to be the source of shells that are a characteristic feature of beaches in the region, especially on Sanibel Island.

Benthic offshore habitats in southwest Florida include hardbottom communities with a diverse epibiota that includes hard and soft corals, macroalgae, and is used by abundant populations of fish species. The hardbottom areas are typically at intermediate depths where limestone outcroppings occur. A thin veneer of overlying sand, when combined with storms and waves, can cause scouring and dislodging of epibiota and transport to barrier island beaches. The shallow depths are colonized by pen shells and quartz sands with shells and other mollusks, such as fighting conchs (*Butrycon* spp.) and calico scallops (*Argopectin* sp.). Deeper depths contain low relief limestone with barrel sponges interspersed with areas of crushed shell and carbonate sediments and occasional *Halophila decipiens*, especially in the Cape Sable Province and northwestern Florida Bay.

There are many attributes of benthic offshore habitats that people care about. In the Barrier Islands Province, beaches are popular shelling destinations. The benthic offshore habitats are the source of the shells, which are transported to the barrier islands during tropical storms and cold fronts. Changes affecting the productive offshore habitats or delivery could threaten the tourism economy. In Lee County, tourism employs one out of every five people, with over five million visitors per year generating over $3 billion in economic revenues (http://www.leevcb.com/statistics/index.php). Commercially valuable fish and invertebrate species (e.g., red drum, pink shrimp, stone crab) use the shelf and estuaries for part of their life cycle and depend on the offshore benthic habitats.

Coastal Wetlands

Within the context of the SWFS ICEM, coastal wetlands are defined as the saltwater zone landward of the coastal margin, which includes the marshes, flats, and mangroves and the intermittent creeks, channels, and rivulets that flow through these areas. The coastal wetlands form a critical ecotone at the boundary between freshwater and marine environments, making them particularly vulnerable to impacts from sea-level rise and changes in intensity and frequency of coastal storms. The IPCC (IPCC, 2007) has identified coastal mangroves and salt marshes as environments that "are likely to be especially affected by climate change" due to "multiple stresses" associated with changing climatic patterns. The four provinces of the southwest coast differ in the nature and extent of their coastal wetlands habitat. The Barrier Islands are predominantly marshes, whereas the region from Ten Thousand Islands south to Cape Sable is described by Davis *et al.* (2005) as "a brackish water ecotone of coastal bays and lakes, mangrove and buttonwood forests, salt marshes, tidal creeks, and upland hammocks." Around Cape Sable and Whitewater Bay, the dwarf mangrove forests are found. The southwest coastal zone includes more than 148,263 acres of mangroves (Smith *et al.*, 1994) and 54,800 acres of salt marshes. NOAA's Coastal Wetlands Inventory (Field *et al.*, 1991) lists the Ten Thousand Islands as having the largest extent of coastal wetlands of any estuarine drainage in the continental United States (2,165,000 acres).

The coastal wetlands of the FSWS region are highly productive in small demersal fishes and invertebrates (Heald *et al.*, 1984; Lorenz, 1999) that, during relatively low water periods, become highly exploited by water bird species (Lorenz *et al.*, 2002; Odum *et al.*, 1982; Ogden, 1994; Powell, 1987) and game fish (Odum *et al.*, 1982; Odum and Heald, 1975). These wetlands also provide critical nesting habitat for water birds (Kushlan and Frohring, 1986; Ogden, 1994) and nursery habitat for fishery species (Ashton and Eggleston, 2008; Comp and Seaman, 1985; Lewis *et al.*, 1988; Manson *et al.*, 2005). In addition, these wetlands enhance the fish biomass on nearby seagrass beds (Manson *et al.*, 2005; Thayer and Chester, 1989), and oysters have been found to assimilate mangrove organic material (Surge *et al.*, 2003; Cannicci *et al.*, 2008), thereby playing a role in seagrass and oyster reef ecosystems. Furthermore, organic export from mangrove forests provides nutrients to surrounding ecosystems (Lugo and Snedaker, 1974; Odum and Heald, 1975; Twilley, 1985, 1988; Nixon, 1980) but mangrove forests, depending on the type, can also sequester nutrients and act as a wastewater filter (Ewel *et al.*, 1998), thereby playing a role in water quality as well.

Ecosystem Services: What People Care About

Ecosystem Services are 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 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.

The MARES project identifies 12 distinct *Ecosystem Services* provided by the SFCME (Table 3). These can be categorized as cultural, regulating, and provisioning 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, fresh water, fiber, biochemicals, and genetic resources. Regulating services and goods are benefits obtained from regulation of ecosystem processes such as climate regulation, disease regulation, water regulation, water purification, and pollination.

The importance of ecosystem services that support recreation and tourism in the SWFS region cannot be overstated. Florida leads the nation as the number one destination for saltwater fishing. Recreational boating is also a very popular

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.

activity. In 2009, Lee and Collier counties had 67,098 registered recreational boats (Florida Fish and Wildlife Conservation Commission, 2010). This is about one boat for every 11 residents, compared with a statewide average of one boat for every 18 residents (Sidman *et al.*, 2009). An economic study of Florida's beaches was compiled with data from 2003 and revealed that over 80 percent of all tourists to southwest Florida visited local beaches (Murley *et al.*, 2003). The annual value of recreational saltwater fishing was estimated at $5.6 billion, statewide, in 2000 (Morgan *et al.*, 2010). In 1995, all tourism and recreation activities, including saltwater fishing, had an annual value of almost $2 billion just in the area covered by the Charlotte Harbor National Estuary Program (Hazen and Sawyer, 1998). This area is at the northernmost extent of the SWFS region. Comparable figures are not yet available for the much larger remaining portion of the region.

Attributes People Care About: Linking State to Ecosystem Services

Ecosystem Services refer to attributes of the coastal marine environment. The value of *Ecosystem Services* derives from the attributes that people care about. The set of "attributes that people care about" combines the idea of "attribute," as a characteristic that reflects the overall condition of the environment, with people's expectations and/or what they consider to be good. "Attributes that people care about" are difficult to define quantitatively compared with environmental parameters that can be simply and directly measured. Nonetheless, they are essential aspects of the benefits that people obtain from the environment and are often directly related to readily-measured parameters.

In general, people care about the sustainability of the coastal marine ecosystem. A sustainable ecosystem is required as the home to particular species that people are interested in, such as sport fish, marine birds, and large animals like sea turtles, dolphins, and mantees that people find engaging and interesting to watch in their native habitat. The attribute of sustainability requires a well-functioning, whole ecosystem in which all elements are healthy and functioning well, e.g., the water column, fish and shellfish populations, coastal wetlands, oyster reefs, seagrasses, and other benthic communities. Fish make use of the entire mosaic of benthic habitats over their life spans. In turn, the communities of organisms responsible for maintaining these habitats require just the right combination of characteristics in the water column, i.e., temperature, salinity, clarity, and nutrient concentrations, to thrive.

In the SWFS region, people are particularly concerned with threats to the quality of inshore and coastal waters. Characteristics of the water column, like clarity and cleanliness, i.e., the general absence of objectionable odor, nuisance, or disease-causing organisms, contributes to the aesthetic appeal of the coastal marine environment as a whole. Water quality is a factor in the main attributes of the coastal marine environment that people care about: the quality of the beaches, the enjoyment of other activities on the water, and the safety of seafood. Red tides, i.e., harmful algal blooms, occur on the SWFS almost every year (Steidinger *et al.*, 1998). In three of the last five years, bloom initiation has occurred in the nearshore coastal waters adjacent to Fort Myers. The Florida Department of Agriculture surveys seafood for health risks related to red tides, and shellfish beds are closed when concentrations of the concentration of *Karenia brevis*, the toxic dinoflagellate responsible for neurotoxic shellfish poisoning (NSP), get too high. Consumers are also concerned about the effects of pollution on the safety of seafood. A recent reduction in seafood consumption in response to the Deepwater Horizon oil spill of 2010 illustrates how perceived effects of pollutants can alter people's attitudes regarding seafood safety.

People care about the size and health of fish and shellfish populations and about maintaining a variety of species in the ecosystem. People care most of all about the species that support fisheries—for this area, the tarpon, snook, red drum, pompano, snappers, groupers, and other large sport fish, as well as pink shrimp and stone crabs. Additionally, most fishermen understand the importance of a diverse and abundant prey base to support their principal species of interest. People also can connect good fishing to productive, relatively undisturbed nursery habitat for fishery species and their prey. Commercial fisheries in the Ten Thousand Islands are focused on blue crab inshore and pink shrimp, stone crab, snapper, and grouper offshore. The two major shrimp trawling grounds are offshore near the Dry Tortugas and near Sanibel-Captiva. Shrimp trawling also occurs in waters where there is an absence of reefs between the two main areas.

The Ten Thousand Islands area provides important habitat for endangered species, two fish species, one marine mammal, and five turtle species that are endangered, threatened, or otherwise of special concern. The threatened wood stork, *Mycteria americana*, also forages in the Ten Thousand Islands (Browder, 1984).

People care about benthic habitats. The intertidal and shallow water areas of inshore flats serve as feeding grounds for fish and marine birds. Healthy SAV communities provide food and habitat for ecologically and economically important aquatic organisms, such as redfish, pink shrimp, and blue crab. SAV grazers include blue crabs (*Callinectes sapidis*) (Zieman, 1982), invertebrates (Lodge, 1991; Newman, 1991), fish (Agami and Waisel, 1988), and the endangered West Indian manatee (*Trichechus manatus*) (Koelsch and Pitchford, 1998).

Oyster reefs support diverse fish populations, crustaceans, and other invertebrates; they mitigate coastal erosion and boat wakes; provide critical nursery and food habitat for recreationally- and commercially-important species; act as a natural filter for phytoplankton, detritus, bacteria, and contaminants in the water column; and sequester carbon in their shell. The “live bottom” and other benthic offshore habitats on the continental shelf are thought to be the source of the shells that make up the beaches in the region and contribute to people’s enjoyment of them.

People care about coastal wetlands because they provide tremendous functional, economic, and ecologic value including: (1) shoreline stabilization and storm protection; (2) flood protection; (3) water quality improvement through the filtering of nutrients; (4) critical habitat for wildlife and marine organisms, including threatened and endangered species, in at least some stage of their life cycles; and (5) aesthetic, educational, sport, and tourist value (Field *et al.*, 1991; Odum *et al.*, 1982). Mangroves provide critical habitat in the life cycle of many important commercial and recreational fishes as both shelter and detritus-based food sources (Estevez, 1998; Heald *et al.*, 1984; Lugo and Snedaker, 1974; Odum *et al.*, 1982). Salt marshes also serve as important nursery and feeding grounds for estuarine animals (Montague and Wiegert, 1990). Coastal food webs are supported by the regional movement of organic matter from coastal marshes to the estuarine and marine systems (Nixon, 1980). Important species include oysters, blue crabs, Caribbean spiny lobsters, pink shrimp, snook, mullet, menhaden, red drum, spotted sea trout, snapper, tarpon, ladyfish, jacks, and others (Odum *et al.*, 1982). The characteristic plant species of the coastal wetlands form critical habitat for a number of vertebrate and invertebrate species (Odum *et al.*, 1982), including seven species and four subspecies listed by U.S. Fish and Wildlife Service as endangered, threatened, or of concern (Odum and McIvor, 1990).

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, recreational boating is a popular activity in southwest Florida, where it is one of the principal means by which people use the coastal marine environment (Sidman *et al.*, 2009). Recreational boating, recreational fishing, other related water activities, and support activities onshore generate economic benefits for the region worth several billion dollars per year (cf. Hazen and Sawyer, 1998). This economic benefit depends critically on the quality of the SWFS coastal marine environment that people travel to enjoy. It also depends on facilities to provide large numbers of people with access to the water, such as boat ramps, marinas, roads, bridges, and dredged channels. Providing these facilities necessarily alters the marine environment, which often conflicts with the objective to maintain the self-sustaining, natural marine ecosystem that people value.

Ecosystem Services that have a supportive function within the ecosystem, such as biodiversity, nutrient cycling, and soil formation, have an indirect, less commonly understood relationship to people’s welfare. Evaluating these services is problematic with valuation techniques that require direct expressions of value. In these circumstances, it may be necessary to construct values indirectly, by tying services to things people directly value. Non-monetizing methods do not require a connection between values and money, but still provide information about relative values, equivalencies, or rankings. The equivalencies and relative ranking methodologies can be used to weigh changes in ecological services resulting from management decisions.

A simple conceptual model of the economics of natural resource and environmental change is provided in Leeworthy and Bowker (1997). 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.

Market values are (1) the expenditures made by users to participate in a recreation activity such as fishing, and (2) the dollar value of commercial fish and shellfish purchases. Non-market values are those values that are not directly observable in a market and include the use value of a recreation activity such as fishing that is the net of the expenditures made to participate in the activity and the non-use value of ecosystem services. Non-use values, also referred to as passive economic use value, is a person's willingness to pay to know that a resource is protected in a certain condition even though the person never plans to directly use the resource. Specific names for non-use values reflect a person's motive for the value. Existence value is the willingness to pay to know that the ecosystem exists in a certain condition. Bequest value is the willingness to pay to leave the ecosystem in a certain condition for future generations.

Another important value is the economic contribution of the ecosystem as it is enjoyed for recreation and to produce goods such as fish and shellfish harvests. Economic contribution is the impact of an ecosystem on recreation expenditures and fish and shellfish purchases including the multiplier effect as this money moves through the local, regional, and state economies of the United States. This economic contribution includes the value of production (output), income, employment, and tax revenues generated in local, regional, state, and U.S. economies.

While benefit-cost analysis using these economic values is an important criterion for measuring the impacts of management alternatives on social welfare, other considerations, including equity, sustainability, ecological stewardship, and cultural and ethical values, are also important to consider in the decision-making process (Costanza and Folke, 1997). Equity analysis requires an estimation of who receives the benefits and who pays the costs of management alternatives. 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).

In addition to the benefits related to recreational boating mentioned above, the SWFS coastal marine ecosystem provides *Ecosystem Services* for wildlife-viewing opportunities; nutrient regulation and filtration; coastal erosion and storm protection; and carbon sequestration.

Wildlife viewing activities contributed approximately $3.1 billion in retail sales to the Florida economy in 2006 with a total estimated economic effect of $5.2 billion (Southwick and Allen, 2008). It is estimated that the region has close to 2000 species of birds, fish, mammals, and other animals (Estevez, 1998). Viewing this diverse wildlife enhances the visitor experience for all tourists, even those who did not travel specifically to view wildlife. Bird watching constitutes one of the largest wildlife-viewing activities (Carver, 2009), and the coastal wetlands and mangrove forests of the southwest coast provide prime opportunities for viewing the diverse community of birds and other animals that utilize the habitat (Estevez, 1998; Montague and Wiegert, 1990; Odum *et al.*, 1982). According to Carver (2009), waterfowl and birds of prey are the largest categories of birds watched away from the home, and these types of birds are abundant in the southwest coastal marshes. In addition, numerous species of birds use the wetlands as wintering or stopover sites during their annual migration (Odum *et al.*, 1982).

Mangroves and coastal marsh systems generally act as filters or traps for a number of elements, including nitrogen, phosphorus, trace elements, and heavy metals through combined interaction of the plants themselves, the soils, and the organisms that live there (Odum and McIvor, 1990; Estevez, 1998; Sklar and Browder, 1998). These elements may be stored in the wetlands for many years. This filtration reduces the amount of nutrients and potential pollutants entering the estuaries and marine system via runoff (Estevez, 1998; Sklar and Browder, 1998).

Mangroves and coastal marshes are a natural barrier to shoreline erosion because the plants trap, hold, and stabilize sediments (Carlton, 1974; Estevez, 1998; Montague and Wiegert, 1990; Odum *et al.*, 1982). In addition, they mitigate the impact of waves and storm surges, providing protection to inland areas (Badola and Hussain, 2005; Montague and Wiegert, 1990; Odum *et al.*, 1982). Barbier *et al.* (2008), in a worldwide study, found that mangroves protected coastal communities from tropical storms up to 5 km inland and that there was an exponential decrease in wave height with increasing mangrove distance inland from the shoreline. For salt marshes, they found a four-fold decrease in wave height with increasing distance inland (Barbier *et al.*, 2008).

Coastal wetlands provide globally important carbon reservoirs. It has been estimated that the litter fall in fringing mangrove swamps of South Florida ranges between 1.86 and 12.98 metric tons ha^{-1} yr^{-1} (Twilley *et al.*, 1986). These environments sequester more carbon per unit area (210 g CO_2 m^{-2} yr^{-1}) than freshwater marshes and peatlands (20-30 g CO_2 m^{-2} yr^{-1}) and release less methane gas because of the abundant presence of sulfates (Chmura *et al.*, 2003).

Overall, very little recent research has been conducted to estimate the value of the SWFS' ecosystem services. The most notable research related to the SWFS, the *Regional Socioeconomic Artificial Reef Project*, was conducted by Florida Sea Grant for the West Coast Inland Navigation District (Swett *et al.,* 2011).

The only other relatively recent study of socioeconomic values of some of the ecosystem services for part of the SWFS was conducted by Hazen and Sawyer for the Charlotte Harbor National Estuary Program (CHNEP) in 1998. The report is entitled *Estimated Economic Value of Resources* (Hazen and Sawyer, 1998). This study concluded that the estimated consumer surplus associated with water-based recreation activities, including fishing and non-use wetland values in the CHNEP study area that includes the coastal and surface water resources of Charlotte, Lee, Sarasota, and Polk counties, was \$3.8 billion in 1998. This value does not include the expenditures made to participate in the recreation activities, which is part of the total value of water-based recreation to users. This study is still cited in CHNEP documents, in particular, the 2009 Comprehensive Southwest Florida/Charlotte Harbor Climate Change Vulnerability Assessment prepared by the Southwest Florida Regional Planning Council and the CHNEP (Technical Report 09-3).

Response: Taking Action

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

Protected Areas

Everglades National Park

Coordinated efforts to preserve the Florida Everglades as wilderness started early in the 20th century with the creation of protected areas (Figure 14). In 1916, Royal Palm State Park, located around the Royal Palm hammock about halfway between Florida City and Flamingo on the old Ingram Highway, was designated. Everglades National Park grew from this nucleus to enclose most of its current extent when dedicated in 1947. Goals for management of the park are to set aside a permanent wilderness, preserving essential

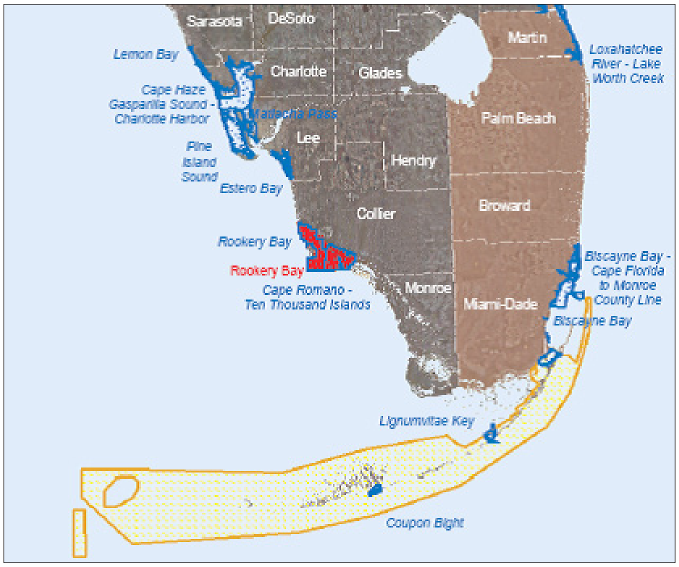


Figure 14. Protected natural areas in the Southwest Florida Shelf region.

primitive conditions including the natural abundance, diversity, behavior, and ecological integrity of the unique flora and fauna. This was the first national park dedicated for its biologic diversity. Establishment of Everglades National Park protected the southern half of the coast along the SWFS region from the direct effects of coastal development.

National Wildlife Refuges

J.N. "Ding" Darling National Wildlife Refuge Complex: The J.N. "Ding" Darling National Wildlife Refuge complex in Lee County consists of the Darling Refuge, located on Sanibel Island, and the nearby Caloosahatchee, Island Bay, Matlacha, and Pine Island National Wildlife refuges. The Darling Refuge was established in 1976 and encompasses 5200 acres of undeveloped mangrove forest. The refuge complex is managed to provide wildlife habitat, with special attention to providing habitat needed by the spring and fall migration of shorebirds.

Ten Thousand Islands National Wildlife Refuge: The Ten Thousand Islands National Wildlife Refuge in Collier County is located at the northern extend of the Ten Thousand Islands Province. The 35,000-acre refuge was established in 1996, and it surrounds the town of Marco Island and includes the Rookery Bay National Estuarine Research Reserve. Approximately two-thirds of the reserve is mangrove forest. The landscape in the remaining portion of the reserve is brackish marsh interspersed by ponds and hammocks of oak, cabbage palm, and tropical hardwoods. The refuge provides a habitat for endangered and threatened species, including the West Indies manatee, bald eagle, peregrin falcon, wood stork, and the Atlantic loggerhead, green, and Kemp's Ridley turtles.

Florida State Parks

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

- Barefoot Beach State Preserve
- Cayo Costa State Park
- Charlotte Harbor Preserve State Park
- Delnor-Wiggins Pass State Park
- Estero Bay Preserve State Park
- Mound Key Archeological State Park
- Stump Pass Beach State Park

Florida State Aquatic Preserves

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

- Cape-Romano–Ten Thousand Islands Aquatic Preserve
- Estero Bay Aquatic Preserve
- Mattacha Pass Aquatic Preserve
- Gasparilla Sound–Charlotte Harbor Aquatic Preserve
- Cape Haze Aquatic Preserve
- Pine Island Sound Aquatic Preserve

Ecosystem Research and Monitoring

Rookery Bay National Estuarine Research Reserve

The Rookery Bay National Estuarine Research Reserve in Collier County is located at the northern extent of the Ten Thousand Islands Province. The reserve encompasses 110,000 acres of mangrove forest, upland and estuarine, and inshore coastal waters surrounding the town of Marco Island. The Florida Department of Environmental Protection and

NOAA jointly manage research at the reserve. The goal is to provide information needed in management decisions for ecosystem restoration and coastal management, education, and outreach to promote coastal stewardship.

Charlotte Harbor National Estuary Program

The Charlotte Harbor National Estuary Program coordinates management activities to improve water quality and ecological integrity of the Greater Charlotte Harbor estuarine system. The geographic area covered by this program, 4,700 square miles, encompasses the estuarine waters of Charlotte Harbor, Lemon Bay, and Estero Bay, and the watersheds of three large rivers: the Myakka, Peace, and Caloosahatchee. The governing management council for the program represents citizens, non-profit groups, and the state and federal agencies responsible for environmental management in the area.

Hydrologic Restoration

The Southwest Florida Water Management District and the South Florida Water Management District implement Florida state water policy through various programs. Ongoing programs that affect the SWFS coastal marine ecosystem include the Lower Charlotte Harbor Surface Water Improvement and Management (SWIM) Plan, the Caloosahatchee River minimum flows and levels criteria, and the Picayune Strand restoration project.

The Lower Charlotte Harbor SWIM plan implements a watershed-based approach to protect the estuarine and nearshore waters of Charlotte Harbor from impacts of point and non-point source pollution and the resulting loss of aquatic habitats. The plan outlines initiatives related to mitigating sources of pollution, restoring a more natural hydrologic regime for freshwater inflows by managing stormwater, implementing a watershed master plan, and protecting and restoring SAV and shellfish habitats in the estuary.

The Caloosahatchee River minimum flows and levels criteria prescribe minimum flows that must be maintained in the Caloosahatchee River during drought to avoid significant harm to the ecology of the river and estuary. Flows in the Caloosahatchee River are controlled by regulating discharge from Lake Okeechobee through the S-79 structure, upstream from Fort Myers. It is recognized that setting minimum flows alone does not suffice to avoid significant ecological harm to the river and estuary. Maximum flow criteria are also being considered in implementing a regional water supply plan, which includes setting a maximum water level for Lake Okeechobee.

The Picayne Strand restoration project is a component of CERP, the cooperative effort led by the South Florida Water Management District and the U.S. Army Corps of Engineers to restore a more natural hydrologic regime in the remaining portion of the Florida Everglades. Restoring the hydrology of the Everglades benefits the coastal marine environment impacted by altered freshwater inflows. The Picayune Strand project seeks to reverse hydrologic changes on a large tract of land in Collier County that was drained for development. The restoration project is plugging the drainage canals. This will increase groundwater recharge, reduce the large, unnatural inflows into the downstream estuaries, and improve estuarine water quality.

Regulation of the Commercial Fishery

The story of fisheries activity in Collier and Lee counties is one of moving from unregulated fisheries to overfishing and subsequent management with regulations. This story is written in the landings data, which show the effects of changes in fisheries management. Fishery landings data maintained by the National Marine Fisheries Service, Southeast Fisheries Science Center, in collaboration with the Florida Fish and Wildlife Conservation Commission, started in 1962 and are ongoing. The landings data show the highest landings in the earliest years of the fishery, a gradual decline in response to a fished stock, and a more abrupt decline when regulations went into effect (Table 4).

Different species have dominated the landings almost by decades. In offshore fishing, mackerel was king in the 1970s before the fishery was declared seriously overfished in the 1980s, and a series of state and federal regulations gradually were set in place. Pink shrimp, caught on both Tortugas and Sanibel grounds, became king of offshore landings in Lee County. Red grouper and other snapper and grouper species became a prominent part of the landings from the SWFS in the mid 1980s. These species declined, however, when gear restrictions and other regulations were imposed on both state and federal waters in the mid 1990s. The use of bottom

Table 4. Average annual landings and ex-vessel value, by decade, in Collier and Lee counties.

	Collier		Lee	
Year	Pounds	Dollars	Pounds	Dollars
1962-1970*	7,030,288	856,439	17,210,931	4,270,830
1971-1980	4,977,514	1,983,576	16,381,833	10,516,951
1981-1990	4,694,588	5,319,458	13,139,891	15,136,392
1991-2000	4,095,861	6,869,130	10,520,219	17,372,006
2001-2010	1,940,075	5,042,877	6,259,558	11,097,070

*The first year of the decade is missing from the first period 1962-1970.

trawls for catching reef fish species was prohibited, and fish traps were banned in 2005.

Silver mullet was the major fishery species in inshore waters in both Collier and Lee counties until the monofilament gillnet was banned for use in most fishing operations in state waters by Constitutional amendment and became effective statewide in 2003. Mullet dominated landings records in both Collier and Lee counties in the first four decades of the record, almost always accounting for more than 2 million pounds annually in Collier County landings and 4 million pounds annually in Lee County landings. The gillnet ban affected not only mullet landings, but also commercial catches of other inshore species such as spotted seatrout, pompano, and crevalle jack. These species are still caught in southwest Florida, but on a smaller scale.

Based on both landings and value averaged for the past 10 years, stone crab claws, taken from offshore waters, are the leading fishery product in Collier County today. Other major species in offshore landings in Collier County are king, cero, and Spanish mackerel (combined landings), pompano, sharks of various species, and Caribbean spiny lobster. Striped mullet (marketed as flesh and roe) and blue crab are the major species harvested from inshore waters and landed in Collier County today. Averaged for the past 10 years, these species alone make up more than 96 percent of the ex-vessel landings value in Collier County, i.e., $1,871,261.

Pink shrimp is the major fishery species landed in Lee County, making up 51 percent of landings as food shrimp, followed by red grouper and stone crab claws offshore and striped mullet (marketed as flesh and roe) and blue crab inshore. Other species contributing the most to Lee County landings are tenpounders, brown shrimp (probably brought into the region from the northen Gulf of Mexico by migrating shrimp vessels), shrimp harvested as bait, rock shrimp, pompano, mojarras, and crevalle jack. Together, the above species make up slightly more than 95 percent of Lee County landings. With a few other species of higher value (i.e., gag and black grouper, Atlantic littleneck and middleneck clams, king and cero mackerel, and pinfish), they make up almost 98 percent of Lee County landings value.

While total landings decreased by decade, ex-vessel values increased through the next to last decade (1991-2000) in both Collier and Lee counties (Table 4). Decreases in landings of stone crab claws, blue crab, striped mullet, king and cero mackerel, and red grouper appear to be the reason for the decrease in Collier landings in the last decade. A large reduction in red grouper landings, a slight reduction in blue crab landings, and a decrease in the average price of shrimp appear to be the main reasons for the decline in ex-vessel fishery value in Lee County in the last decade (2001-2010).

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Water Column

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In a nutshell:

- The quality of coastal marine waters determines the primary productivity of the ecosystem that is available to support populations of fish and shellfish.
- Conditions in the water column affect the quality of beaches for tourism, the safety of seafood, and the availability of habitat needed by several endangered species.
- Circulation patterns on the SWFS limit exchange and favor the development of algal blooms and their retention in nearshore waters for periods of weeks to months.
- Inputs of nutrients related to agriculture and development might be responsible for increasing the occurrence of harmful algal blooms in marine waters; however, this is a topic of debate among scientists.

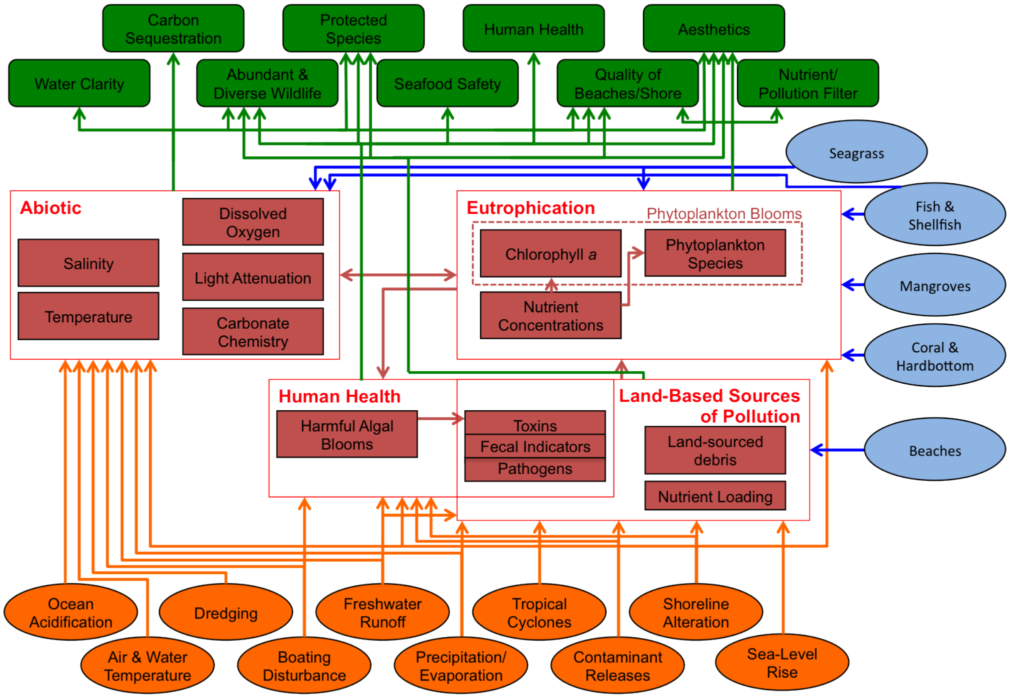
The water column of the SWFS reflects the inflow of freshwater from the Florida peninsula, the physical processes that control surface circulation, and the complex biogeochemical processes that influence the cycling and concentration of particulate and dissolved materials. The geographical limits of the domain of interest extend from the inner low-salinity waters adjacent to the coast to the outer boundary of shelf waters set by a barrier to lateral mixing known as the "forbidden zone" (Yang *et al.,* 1999; Olascoaga *et al.,* 2006). The southern boundary includes the waters offshore of the Ten Thousand Islands while the northern boundary is offshore of Charlotte Harbor. A diverse set of sources and sinks of the dissolved and particulate constituents in the water column occur at the boundaries of these shelf waters and include bottom sediments, the contiguous oceanic waters of the Gulf of Mexico, and the riverine inflows along the west Florida coast. The organisms included in this model encompass plankton (phytoplankton, zooplankton, bacteria, and other "decomposers") but exclude the benthos and larger living resources such as invertebrates and fish. These larger organisms are incorporated into the fisheries submodel for the SWFS.

There are persistent offshore spatial gradients in physical properties (salinity) and the dissolved and particulate materials from the coast to outer shelf waters, with maximum concentrations of dissolved and particulate materials near the coastal inflows and estuaries. The constituents are modified through biogeochemical cycling in both the water column and the sediments. Residence times of dissolved and particulate matter on the shelf can be on the order of weeks to months as the flow regime constrains surface waters onshore of the convergent boundary at mid-shelf (Yang *et al.,* 1999). Thus, two of the ecosystem attributes that people care about, harmful algal blooms dominated by the toxic dinoflagellate *Karenia brevis* (Steidinger *et al.,* 1998) and "blackwater" events (Hu *et al.,* 2003), can be retained on the inner shelf and influence water quality for periods of weeks to months.

Role in Ecosystem: The Water Column Linkages to Water Quality and Fisheries

The spatial distribution and abundance of pelagic and benthic primary producers are critical components of the SWFS ecosystem. The magnitude of primary production determines the quantity of organic matter available to support higher trophic levels. The surface waters of the West Florida Shelf are oligotrophic, except for the nearshore regions in which freshwater discharge delivers nutrients in river plumes that are derived from natural and anthropogenic sources. Pelagic fish are dependent upon sufficient phytoplankton production for organic matter, but are also influenced by the species that are present. The highest levels of pelagic primary production (fish and shellfish) on the West Florida Shelf occur in blooms of the dinoflagellate *Karenia brevis* (Vargo *et al.,* 1987), a harmful algal species that producers brevetoxins. However, when these toxins accumulate in shellfish, or in the flesh of finfish, they result in Neurotoxic Shellfish poisoning (NSP) due to their neurotoxic properties (Watkins *et al.,* 2008). Consumption of fish with brevetoxins can result in the deaths of birds, fish, and marine mammals. Additionally, the release of brevetoxins in the atmosphere can lead to respiratory distress with symptoms that result in treatment within hospital emergency rooms (Hoagland *et al.,* 2009). The magnitude of nutrients required to support these blooms, as well as other pelagic primary producers, is an active area of research with societal implications.

Water quality also is a function of water clarity. The quantity and quality (spectral composition) of irradiance that penetrates the water column determines the magnitude of benthic primary production. Benthic primary producers



Water column submodel diagram for the Southwest Florida Shelf.

include seagrass and the microphytobenthos; these organisms contribute to total ecosystem production in the mid and northern segments of the West Florida Shelf (Gattuso *et al.,* 2006). However, the magnitude of primary production in benthic versus pelagic environments is not well documented for the SWFS. Given the results of model experiments for shelf waters off Tampa Bay (Darrow *et al.,* 2003), it is likely that benthic primary production is potentially equivalent to that in the water column. Nutrient inputs influence the distribution of primary production, for enhanced pelagic primary production can reduce the available light energy reaching the benthos. If phytoplankton growth is stimulated by enhanced nutrient delivery from freshwater sources, the magnitude of benthic primary production can decrease as light becomes limiting for photosynthesis on the bottom.

Attributes People Care About

The water column of the SWFS plays a major role in the attributes that people care about. The ecosystem services provided by the pelagic ecosystem are strongly linked to the water column. Among these attributes are:

- Harmful algal blooms
- Beach quality
- Water clarity
- Protected species
- Seafood safety

Harmful Algal Blooms

Harmful algal blooms occur on the SWFS almost every year (Steidinger *et al.,* 1998). Bloom initiation can occur offshore in subsurface waters below the thermocline. Cells adapted to low light conditions are transported eastward, towards the coast, in the bottom waters in response to forcing by prevailing winds. The highest cell concentrations develop nearshore adjacent to the coastal salinity fronts in response to a combination of physical, chemical, and biological processes (Walsh *et al.,* 2006). In three of the last five years (2007-2011), bloom initiation has occurred in the nearshore coastal waters adjacent to Fort Myers. Blooms were subsequently transported north by alongshore currents that responded to forcing by prevailing winds. Eventually the blooms declined, with remnants of *K. brevis* populations near Fort Myers.

Declining blooms can be exported from the SWFS. In the late fall or early winter, currents can transport the remnant populations south to the Florida Keys and eventually carry *K. brevis* to offshore waters (Walsh *et al.,* 2009; Olascoaga *et al.,* 2006). When the cells are transported offshore, they can be exported to the Florida Current and eventually be advected around the Florida Keys to the East Florida Shelf (Murphy *et al.,* 1975). Periodically, harmful algal blooms dominated by *Karenia* spp. develop along the southeast Florida coast and infrequently develop as far north as Cape Hatteras (Tester *et al.,* 1991).

Beach Quality

Tourism is the main source of income in southwest Florida, and beach quality is a major determinant of tourist visits to the area, as well as the quality of their vacation experience. An economic study of Florida's beaches was compiled with data from 2003 and revealed that over 80 percent of all tourists to southwest Florida visited local beaches (Murley *et al.,* 2006). Income from tourism in southwest Florida, from Charlotte to Sarasota counties, exceeded $15 billion, with approximately half from direct spending. If beach quality degrades, visits to beaches rapidly decline for both local inhabitants and tourists.

Water Clarity

The clarity of the water column is determined by the particulate and dissolved constituents. The oligotrophic nature of the water column implies that throughout much of the year the water is highly transparent. However, inputs of terrestrial dissolved organic matter and nutrients alter water clarity on the SWFS through the direct contribution of colored dissolved materials and the stimulation of phytoplankton growth (Bissett *et al.,* 2005). These constituents can degrade the transmission of light through surface waters and alter water clarity. Phytoplankton booms, including harmful algal blooms, are one of the features that the public identifies as responsible for altering water clarity.

Protected Species

The SWFS is one of the major regions in which manatees overwinter. In 2009, the Florida Fish and Wildlife Conservation Commission reported that there were >2400 manatees in the nearshore waters of the southwest coast, with an approximately equal number along the east coast of Florida. Many of the overwintering mammals reside near Fort Myers, particularly the Florida Power and Light power plant. When the mammals are in coastal waters, they are prone to injury from power boats. Additionally, manatees suffer when harmful algal blooms occur. A bloom of *Karenia brevis* killed over 50 mantees in 1996 (Bossart *et al.,*1998), with an additional mortality event, at reduced numbers, in 2000 (Bossart, 2001). Turtles are also found in the coastal waters of the SWFS, with nesting beaches for loggerheads in Naples and Bonita Springs beaches from May to October. The most endangered sea turtle in the world, the Kemp's Ridley, nests in the Ten Thousand Islands region and Charlotte Harbor. Radio satellite tracking studies of a few of these turtles have found that when adults migrate into coastal waters, they can remain within Florida's water throughout the year (http://www.conservancy.org/page.aspx?pid=585).

Seafood Safety

Floridians consume about 40 pounds of seafood per person annually, about twice the average per capita consumption in the United States (Degner *et al.,* 1994). Consumers are concerned about the safety of seafood, and a recent reduction in seafood following the Deepwater Horizon oil spill in 2010 illustrates how perceived effects of pollutants can alter public attitudes regarding seafood safety. The Florida Department of Agriculture surveys seafood for health risks. On the southwest Florida coast, this monitoring includes sampling the ambient seawater concentration of *Karenia brevis*, the toxic dinoflagellate responsible for NSP with symptoms of diarrhea, nausea, and vomiting. Shellfish beds are closed when cell concentrations reach 5,000 cells liter^{-1}. This management policy has been effective, with typically one to five cases diagnosed during blooms (Watkins *et al.,* 2008).

Quantifiable Attributes

Nutrient Concentrations

Nutrient and dissolved organic matter concentrations decrease from the coast to offshore waters along the southwest Florida coast. Nutrients are altered on the shelf as primary production incorporates inorganic forms into organic matter, which are subsequently recycled through decomposers, predominantly bacteria, to inorganic nitrogen and phosphorus. Rates of nutrient cycling have been assessed for both nitrogen and phosphorus in conjunction with algal blooms, particularly in the region between Charlotte Harbor and Tampa Bay, as summarized by Vargo *et al.* (2008). The anthropogenic contribution of nutrients to coastal waters has been hypothesized to enhance the frequency of harmful algal blooms along the SWFS (Brand and Compton, 2007), although the extent of the linkage between development and bloom occurrence is under debate (Vargo, 2009; Walsh *et al.,* 2009).

The nearshore distribution of salinity reflects the wind-driven circulation and input of freshwater from rivers. Liu and Weisberg (2007) mapped the salinity distribution across the shelf off Tampa Bay and Sarasota. The seasonal pattern of salinity along the coast revealed low salinities (<35.9) shoreward of the 30-m isobath in summer, with higher salinities (>36) present in winter. During the winter, the inner shelf currents are to the southeast and upwelling is favorable, while in summer downwelling occurs with currents to the northwest. Sutton *et al.* (2001) similarly found that lowest salinities were shoreward of the 30-m isobath in the midwest Florida Shelf.

In the southern region of the SWFS, the gradients in the concentrations of nitrogen and phosphorus (Rudnick *et al.,* 1999) and silica (Jurado *et al.,* 2007) have been assessed with regard to the alongshore flux from rivers to western Florida Bay. Quantifying the nutrient flux from the SWFS to western Florida Bay is important to accurately monitor the effects of Everglades restoration efforts on productivity of the bay and surface waters of the adjacent shelf (National Research Council, 2008).

Chromophoric Dissolved Organic Matter

The cycling of organic matter in the surface waters of the SWFS has been evaluated in the context of the contribution of chromophoric (colored) dissolved organic matter (CDOM) to inorganic carbon inputs (Clark *et al.,* 2004). Terrestrial sources of CDOM are decomposed in the upper water column by a combination of physical (photodegradation), biological (microbial decomposition), and chemical processes as fresher waters are mixed with saltier waters on the shelf. The most refractory matter remains in the water column as more labile material is degraded. This material contributes to the high extinction coefficients (low visibility) associated with blackwater events that originate from freshwater sources and propagate across the SWFS.

Phytoplankton Blooms

While harmful algal blooms are of major concern on the SWFS, other non-toxic species also create dense populations of high algal biomass in surface waters. Diatoms are a beneficial food source for many marine organisms, including benthic invertebrates, and are frequently present at bloom concentrations on the SWFS. Nutrient quality and quantity appear to regulate the dominant phytoplankton taxa present along the SWFS. Under conditions of low riverine inputs, northern waters have relatively low inorganic nitrogen concentrations in conjunction with cyanobacteria and dinoflagellate-dominated communities. In mid-shelf waters (Sanibel to Shark River), the nitrogen:phosphorus ratios are near that required to support plankton growth with cyanobacteria dominating. In southern waters (south of Shark River), diatoms can dominate under phosphorus-depleted conditions (Heil *et al.,* 2007).

Diatoms require silica in contrast to other phytoplankton taxa that lack frustules, the external siliceous "covering" of diatoms. The silica input to the SWFS from rivers (Juardo *et al.,* 2007) and potentially from groundwater (Brand, 2002) favor the growth of diatoms on the southern SWFS. Centric diatom blooms have developed in nearshore waters adjacent to Charlotte Harbor (McPherson *et al.,* 1990), the SWFS adjacent to the Ten Thousand Islands (Jurado *et al.,* 2007), and in the shallow regions of western Florida (Phlips and Badylak, 1996). These blooms are advected south along the shelf in the fall, creating winter diatom blooms in western Florida Bay.

Toxins

The toxic nature of *Karena brevis* blooms results from the production of a suite of polyether neurotoxins that are collectively termed brevetoxins. These high molecular-weight compounds can accumulate in shellfish and, when consumed in sufficient concentrations, produce symptoms (gastric distress) termed NSP (Watkins *et al.,* 2008). The toxins can also be transferred across the air-sea interface and then aerosolized. When the aerosolized brevetoxins are inhaled by beachgoers, they produce symptoms of rhinorrhea, coughing, and severe bronchoconstriction (Kirkpatrick *et al.,* 2004). The resulting costs associated with toxic blooms are estimated to range from 0.5 to 4 million dollars annually in visits to hospital emergency rooms in Sarasota County, Florida (Hoagland *et al.,* 2009). Medical costs associated with *K. brevis*-related respiratory illness are undoubtedly much higher for the entire west Florida coast.

Drivers of Change in the Southwest Florida Shelf

Development

The coastal counties of southwest Florida have experienced rapid population growth during recent decades. Between 2000 and 2008, for example, the population of Sarasota and Collier counties increased at a rate at, or exceeding, 10 percent. This increase has been hypothesized to have resulted in enhanced nutrient discharge to the coastal waters of the SWFS and an increase in the occurrence of harmful algal blooms (e.g., Brand and Compton, 2007). Eutrophication has been demonstrated to enhance development of harmful algal blooms in other regions (Anderson *et al.,* 2008), although the specific linkage between coastal eutrophication and harmful algal bloom occurrence on the West Florida Shelf is in debate (Walsh *et al.,* 2009; Vargo, 2009).

Climate Change

The increase in surface temperature of marine surface waters associated with the anthropogenic input of carbon dioxide to the atmosphere has several potential effects on marine ecosystems. The impact of an alteration in the carbon dioxide system in seawater will affect marine organisms that produce calcium carbonate as aragonite in skeletal structures (Andersson and Gledhill, 2011). The impact of this effect on the SWFS could potentially be in the species composition of the benthic community, although there have been no studies to address this. A second potential impact of climate change could be in a species shift in the pelagic communities, particularly in the species composition of phytoplankton. Changes in land runoff due to modification of the hydrologic cycle, coupled with altered inputs of nutrients and a warming of surface waters, have been proposed to result in changes in species in phytoplankton taxa (Paerl and Scott, 2010; Hallegraeff, 2010).

Nutrient Loading

Several sources contribute nutrients to the water column of the West Florida Shelf, including rivers, benthic communities, and bottom intrusions that originate from onshore flows from the Gulf of Mexico Loop Current. Considerable effort has been devoted to quantify the nitrogen and phosphorus inputs from these sources as they support harmful algal blooms on the SWFS. Estuaries are a major source of nutrients, in both dissolved inorganic and organic forms, that support primary production near the shore (Vargo *et al.,* 2008). In particular, dissolved organic forms of nitrogen are the major form of this essential nutrient in the rivers that flow into the West Florida Shelf coastal waters (McPherson and Miller, 1990).

Further offshore, nitrogen and phosphorus enter the shelf ecosystem from upwelling of subsurface waters in the Loop Current (Walsh *et al.,* 2006). Additional biological inputs occur from the nitrogen-fixing cyanobacteria *Trichodesmium* sp., which often blooms in summer in response to the seasonal input of iron from atmospheric dust transported westward from the Sahara (Walsh and Steidinger, 2001). When *Trichodesmium* sp. blooms, they release measurable quantities of dissolved organic nitrogen that subsequently supports primary production in the water column. Direct atmospheric inputs of nitrogen also occur through wet and dry deposition in the eastern Gulf of Mexico (Paerl *et al.,* 2002). In total, these sources can support dense algal blooms on the West Florida Shelf, although no individual nutrient source is sufficient to maintain prolonged bloom events (Vargo *et al.,* 2008).

Tropical Cyclones

Tropical cyclones occur almost annually in the Gulf of Mexico. These event-scale features can rapidly transit through the West Floria Shelf in mid to late summer. Mixing is greatly enhanced during the passage of these storms, and surface waters can be destratified with nutrients introduced into the surface layer (e.g., Ortner *et al.,* 1984). Primary production is enhanced in the wake of intense storms, although this effect is primarily observed in oceanic waters seaward of the shelf break (Chen *et al.,* 2009). In nearshore waters, the passage of intense storms can resuspend sediments and reduce the transparency of the water column (e.g., Chen *et al.,* 2009), resulting in a potential reduction in pelagic primary production in coastal waters.

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Fish and Shellfish: Fish, Shrimp, and Crabs

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In a nutshell

- The SWFS region provides essential habitat for many kinds of fish, shellfish, and marine animals, including the endangered smalltooth sawfish, goliath grouper, bonnethead, blacktip, lemon and nursery sharks, the Kemp's ridley, green, leatherback, and Atlantic loggerhead sea turtles, and the West Indian manatee.
- The fish and shellfish resources of this region support valuable recreational and commercial fisheries.
- Freshwater inflow to the coast influences salinity, temperature, turbidity, nutrient concentrations, and other conditions that are important to the animals that depend on inshore habitat for food and as nursery areas.
- Water management practices adopted to promote expansion of agriculture and urban development throughout the South Florida region have altered the quantity, quality, timing, and distribution of freshwater inflows to the southwest Florida coast.

Define Resource

The fishery resources of the SWFS are highly valued and protected to various degrees by the Ten Thousand Islands National Wildlife Refuge, Rookery Bay National Estuarine Research Reserve, Fakahatchee State Park, and Everglades National Park. The fish and macroinvertebrate fauna of the Ten Thousand Islands support both recreational and commercial fishing. The short list of target species inshore includes snook, tarpon, red drum, spotted seatrout, pompano, and sharks. Offshore, the principal target species are snapper, grouper, cobia, permit, barracuda, king and Spanish mackerels, and more sharks.

The Ten Thousand Islands area west of Chokoloskee consists of a series of inner open water areas, called bays, separated from the Gulf of Mexico by a broader area of small mangrove islands surrounded by shallow water. The wetlands that grade into the bays from the uplands are covered primarily with red mangrove. Mangrove-lined passes connect the inner bays and inter-island areas with the Gulf of Mexico, except immediately south of Cape Romano where a large shallow open-water outer bay, Gullivan Bay, lies between the islands and the Gulf of Mexico. The easternmost and largest of the inner bays is Fakahatchee Bay, which historically received the natural freshwater discharge of East River and the Fakahatchee River, both of which are tributaries of Fakahatchee Strand and the Okaloacoochee Slough, a major natural shallow-water freshwater-flow system.

The principal sport fishing targets represent a small component of the fish and shellfish of Ten Thousand Islands waters. Inshore are many other fish that provide good opportunities for anglers, as well as a myriad of smaller fish that serve as bait for anglers and the prey of fishing targets. The first category includes spotted and sand seatrout, sheepshead porgy, and hardhead catfish. In a two-year trawl study of Faka Union, Fakahatchee, and Pumpkin bays, Browder *et al.* (1986) documented at least 79 fish species and 70 macroinvertebrate species that fit the lower and middle levels of the faunal food web. Dominant fish were bay anchovy, yellowfin menhaden, scaled sardine, striped anchovy, pinfish, and silver perch. In a later three-year study of Faka Union and Fakahatchee bays and Henderson Creek, Shirley *et al.* (2005) listed as dominants spotfin mojarra, silver jenny, fringed flounder, pigfish, and blackcheeked tonguefish. Pink shrimp were among the numerically-dominant species in Shirley *et al.* (2005), and the total catch of pink shrimp was of similar magnitude in a 1972 trawl study of Fakahatchee and Faka Union bays by Carter *et al.* (1973). Pink shrimp were the second most abundant decapod, following caridean shrimp in abundance, in Browder *et al.* (1986). Species composition changes seasonally and varies by bay system (Shirley *et al.,* 2005).

Several species of special concern are a part of the aquatic fauna of this region. Southwest Florida is the last stronghold for the endangered smalltooth sawfish, and 619,013 acres of the combined Ten Thousand Islands and Everglades regions have been declared critical habitat for this species. Such designation requires "consultation" on permits and public works plans that might affect the habitat. Waters of the Ten Thousand Islands are also important habitat for the goliath grouper, once an important fishery species. The species was declared "economically overfished" in the early 1990s and placed off limits for fishing ever since. The West Indian manatee is another major endangered species living in the Ten Thousand Islands. Kemp's Ridley, green, leatherback, and Atlantic loggerhead sea turtles are other listed endangered species for which the Ten Thousand Islands are important habitat. These waters also provide nursery habitat for several species of sharks (Patrick Donnell, Mote Marine Laboratory, personal communication), including bonnethead, blacktip, lemon, and nursey sharks.

Role in Ecosystem

The Ten Thousand Islands are an important nursery area for many recreational and commercial species, including some harvested offshore. The Ten Thousand Islands waters are also habitat for resident species that spend their entire life cycle inshore and other species that use the Ten Thousand Islands as nursery grounds. The typical pattern for the latter is offshore spawning, followed by immigration of early life stages to inshore Ten Thousand Islands waters. There are many variations on this pattern. Spawning areas for some are near the outer SWFS; whereas other species spawn just outside the passes, and their eggs are carried inshore on currents. Some species occasionally found in the Ten Thousand Islands are not necessarily totally dependent upon these waters at any particular life history stage but take advantage of the productive and sheltered habitat they provide.

A combination of dynamic and structural features distinguish the habitat of fish and macroinvertebrates. Dynamic features include salinity ranges, nutrient gradients, and other factors that shift around and expand and contract with freshwater inflow and the tide. Structural habitat is fixed in space and associated with the bottom or the shoreline. In the Ten Thousand Islands, three of the most important types of structural habitat—mangrove prop root, seagrass, and oyster bar—are provided by living, or once living, organisms. Such habitat enhances feeding opportunities and provides protection from predators for many species. Habitat needs of individual species may be more specific within each habitat type. For example, mangrove prop root habitat may be tidal creek, edge of a bay, backwater side of an island, or the faster currents of passes, any one of which may be the preferred habitat of a species.

Predation is an important governing factor in ecosystems. By preying on other organisms, fish species operating at several trophic levels create pressures that influence ecosystem structure and function in many ways (Sih *et al.,* 1998), even affecting primary producers, including phytoplankton, epiphyton, and seagrasses. Because in even the simplest cases, fish are players in food webs, not food chains, a change in the abundance of one species can have reverberating consequences. The generally high productivity of estuaries attracts predators. The habitat structure in estuaries provides a counterbalance by providing prey with places to hide. Nevertheless, food supply probably is not limiting to the larger estuarine predators. The role of predation can be better understood by briefly describing some of our upper trophic level predators and some major prey items.

Red Drum

Red drum spawn in the fall (i.e., mid-August through early November) at the mouths of passes, and larvae settle out along the bayshore and then migrate toward low salinity backwater areas, including tidal creeks (Jannke, 1971; Peters and McMichael, 1987). Juvenile red drum gradually move back into the bay with increased size and age. Adults are found in more open waters, except at spawning time, when they move to the mouths of passes. According to Peters and McMichael (1987), red drum prey on copepods as larvae, shifting to mysids once they are >8 mm long and then to caridean and penaeid shrimps (including pink shrimp) when they are >75 mm long. Juveniles >90 mm long eat crabs and fish. Red drum are among the many mobile species that occur in association with oyster reefs.

Snook

The common snook is another important sport fish species of the Ten Thousand Islands. Carter *et al.* (1973) report that the main food items of juvenile snook in the Ten Thousand Islands, by volume, were fish (81 percent), shrimp (16 percent), and crab (2 percent). Dominant prey fish species were poeciliids, cyprinodonts, and atherinids. Younger juveniles ate a mix of zooplankton, fish, and palaemonid shrimp (Carter *et al.,* 1973). Other sport and commercial species found in tidal streams of the Ten Thousand Islands by Carter *et al.* (1973) were spotted searout (*Cynoscion nebulosus*), gray snapper (*Lutjanus griseus*), crevalle jack, sheepshead, striped mullet, pinfish, and striped mojarra.

Tarpon

The tarpon is an internationally renowned big game fish of southwest Florida. It is esteemed for its stamina, strength, and leaping prowness (Zale and Merrifield, 1989). Like many other fish found in southwest Florida estuaries, this species spawns offshore. Sexual maturity is attained at a total length of about 120 cm. Fecundity of a 2-m long female was estimated at 12.2 million eggs. The diet of tarpon changes through life. Stage 1 tarpon absorb nutrients integumentarily from seawater. Stages II and III feed on zooplankton. Juvenile tarpon progressively increase the size of their prey as they grow, feeding initially on insects, crabs, and grass shrimps of the genus *Palaemonetes*, and small fishes in the families Poeciliidae and Cyprinidonidae. Adult tarpon capture larger midwater fish prey, such as mullets, hardhead catfish, Atlantic needlefish, and sardines, as well as shrimp and crabs, which they swallow whole. The closely related lady fish has a similar life history and diet in younger stages but, due to its smaller adult size, does not advance to the larger prey. Although abundant, it is not a targeted sport fish.

Goliath Grouper

The Ten Thousand Islands are a recognized important juvenile nursery habitat for goliath grouper and the center of their distribution (Koening *et al.,* 2007). This species is the largest grouper in the western North Atlantic. It is found from nearshore waters out to depths of 70 m. The larvae settle in Florida estuaries in the fall, and the young are found along mangrove-lined creeks and tidal passes from settlement size up to about 1 meter long and an age of 6 or 7 years (Koenig *et al.,* 2007).

Sharks

The Ten Thousand Islands are an important nursery habitat for sharks. The bull shark is the most numerous shark in Faka Union Bay. It is capable of withstanding low salinities for long periods and moves freely between marine salinities and freshwater. Low salinities may exclude other shark species from entering Faka Union Bay during the wet season. Bonnethead sharks inhabit the Ten Thousand Islands throughout their lives, from neonate stage to adult. Blacktip sharks use the Ten Thousand Islands during their neonate, young of the year, and immature stages. Lemon sharks use the area in their young of the year and immature stages. Nurse sharks are found there in their immature stage.

Smalltooth Sawfish

Coastal mangrove estuaries between Charlotte Harbor and Florida Bay are recognized as premium nursery habitat for the U.S. distinct endangered population of smalltooth sawfish and have been declared “critical habitat” for this species by the National Marine Fisheries Service (effective October 2, 2009, *Federal Register*, Vol. 74, No. 169, pp. 45,353-45,377). This tropical estuarine elasmobranch has a circumtropical distribution. The U.S. population suffered decline and range constriction in the early to mid 1900s and is now restricted to peninsular Florida. Individuals are 80 cm in total length at birth and can grow to 540 cm or greater. Rapid juvenile growth occurs during the first two years from birth. Age at maturity is estimated at 10-20 years, after reaching a total length of 340 cm. Bycatch in various commercial and recreational fisheries is viewed as the primary reason for the decline. They are found very close to shore on muddy and sandy bottoms, often in sheltered bays, on shallow banks, and in estuaries or river mouths, but habitat use is complex and varies by life history stage. Adults are opportunistic feeders and forage on a variety of fish and crustacean species. Juveniles are especially vulnerable to predation and starvation. Their preferred habitat is less than 1 meter in depth.

Pink Shrimp

The pink shrimp, basis of a multimillion dollar fishery in South Florida, is also a principal prey of sport fish and other predators in the Ten Thousand Islands. The pink shrimp spawns offshore and enters South Florida nursery areas such as the estuaries of the Ten Thousand Islands to spend its juvenile life, growing rapidly to late juveniles and young adults and then returning to offshore spawning areas and fishing grounds. Pink shrimp is the documented prey of gray snapper and spotted seatrout (Hettler, 1989). Caridean shrimp, occurring as several species in the Ten Thousand Islands, all smaller than pink shrimp, also serve as prey for many species, including pink shrimp. In complex food webs leading from mangrove and seagrass detritus and planktonic and epiphytic algae (Odum and Heald, 1972; Fry *et al.,* 1999), any one species is supporting symbiotically, competing with, or feeding many others.

Attributes People Care About

People care most of all about the species that support fisheries—for this area, the tarpon, snook, red drum, pompano, snappers, groupers, and other large sport fish, as well as pink shrimp and stone crabs. Additionally, most fishermen understand the importance of a diverse and abundant prey base to support their principal species of interest. People also can connect good fishing to productive, relatively undisturbed nursery habitat for fishery species and their prey.

Fishing is a major objective of Florida visitors whose destination is southwest Florida. The Ten Thousand Islands, the Charlotte Harbor-Caloosahatchee River area, and the SWFS are renowned fishing trip destinations. The spectacular wilderness atmosphere and teeming waters make fishing a major tourist attraction. The labyrinth of inner bays, passes, and outside waters that make up much of the Ten Thousand Islands attract backcountry-fishing enthusiasts from all over the world. Recreational fishing on the SWFS is also popular. Legal-size snapper and grouper can be found offshore over hardbottom areas in waters 40-50 feet deep or more, where gray and lane snapper are mixed with red grouper.

Recreational fishing in the Ten Thousand Islands area includes guide boat fishing, tournament fishing, and fishing from private vessels (Browder *et al.,* 1981). Backcountry fishing guides provide valuable expertise on what, where, and when to fish. Guides experienced with the geography of the area easily navigate the many confusing passes, inter-island channels, back bays, and tidal creeks, where the newcomer to the area can easily become lost. Tournaments such as the Red Snook Charity Tournament and other tournaments announced periodically on the internet by fishing clubs, or by sport fishing magazines, attract many sports fishing participants to the Ten Thousand Islands. Several tournaments that draw sportfishing visitors are organized each year.

The principal targets of inshore sport fishing are tarpon and snook, but spotted seatrout and red drum are also popular. Other species that help make the inshore trip satisfying are sheepshead, pinfish, and mojarras. Sharks are caught recreationally both inshore and offshore. The paying passenger industry is made up of independent captains who operate out of communities with hotels and resorts and also have websites. Clients hear about the fishing opportunities and guides from family and friends who have fished in South Florida. Recreational fishing activity is augmented by visitors that bring their own boats and local recreational fishers.

Commercial fishing is a traditional source of income in southwest Florida. Fishing history is written in the landings data collected since 1962. Different species have dominated the landings almost by decade. In offshore fishing, mackerel was king in the 1970s before the fishery was declared seriously overfished in the 1980s and a series of state and federal regulations gradually were set in place. Pink shrimp, caught on both Dry Tortugas and Sanibel grounds, dominated offshore landings in Lee County. Red grouper and other snapper and grouper species became a prominent part of landings from the SWFS in the mid 1980s, but declined when gear restrictions and other regulations were imposed in both state and federal waters. The use of bottom longlines for catching reef fish species was prohibited inside 20 fathoms in the mid 1990s. Fish trap bans reached Collier and Lee counties in 2007.

Striped mullet was the major fishery species in inshore waters in both Collier and Lee counties until the monofilament gillnet was banned for most fishing operations in state waters by Constitutional amendment and became effective statewide in 1995. Mullet dominated landings records in both Collier and Lee counties in the first four decades of the record, usually accounting for more than two million pounds landed annually in Collier County and four million pounds landed annually in Lee County (compiled from records maintained by NOAA's National Marine Fisheries Service, Miami, FL). The gillnet ban affected not only mullet landings but also commercial catches of other inshore species such as spotted seatrout, pompano, and crevalle jack, which are still caught in southwest Florida, but on a smaller scale.

Based on both landings and value, averaged for the past 10 years, stone crab claws, taken from offshore waters, are the leading fishery product in Collier County today. Other major species in offshore landings in Collier County are king, cero, and Spanish mackerel (combined landings), pompano, sharks (various species), and spiny lobster. Striped mullet (marketed as flesh and roe) and blue crab are the major species harvested from inshore waters and landed in Collier County today. Averaged for the past 10 years, these species alone make up more than 96 percent of ex-vessel landings value in Collier County, i.e., $1,871,261 (compiled from records maintained by NOAA's National Marine Fisheries Service, Miami, FL).

Pink shrimp is the major fishery species landed in Lee County, making up 51 percent of landings as food shrimp, followed by red grouper and stone crab claws offshore and striped mullet (marketed as flesh and roe) and blue crab inshore (compiled from records maintained by NOAA's National Marine Fisheries Service, Miami, FL). Other species contributing the most to Lee County landings are tenpounders, brown shrimp (probably brought into the region from the northern Gulf of Mexico by migrating shrimp vessels), shrimp harvested as bait, rock shrimp, pompano, mojarras, and crevalle jack. Together, the above species make up slightly more than 95 percent of Lee County landings. Pinfish and a few other species of higher value (i.e., gag and black grouper, Atlantic littleneck and middleneck clams, king and cero mackerel, and pinfish), make up another 3 percent of Lee County landings value.

Commercial fisheries in the Ten Thousand Islands are focused on blue crab inshore and pink shrimp, stone crab, snapper, and grouper offshore. Other species such as pompano and king mackerel also are caught offshore. The two major shrimp trawling grounds are offshore near the Dry Tortugas and near Sanibel-Captiva. Shrimp trawling also occurs in shelf waters between the two main grounds wherever reefs are not present.

The passage of the Endangered Species Act and the Critical Habitat component of the Magnuson-Stevens Fishery Conservation and Management Act suggests that people care about species that are imperiled. The Ten Thousand Islands area provides important habitat for at least two fish species (smalltooth sawfish and goliath grouper), one marine mammal (West Indian manatee), and five turtle species (green, loggerhead, Kemp's Ridley, hawksbill, and leatherback) that are endangered, threatened, or otherwise of special concern. The threatened wood stork, *Mycteria americana*, also forages in the Ten Thousand Islands (Browder, 1984).

Attributes We Can Measure

Fishery landings and catch per unit of effort (CPUE) data may provide the best long-term measure of the biological productivity and well-being of southwest coast estuaries and offshore waters. Although landings data can be affected by changes in regulations, CPUE data are less affected by such changes, as long as the same gear are operating. Landings data for some species have been collected in Lee and Collier counties since 1962. Other species were gradually added to the record, and landings data have been collected for most species since at least the 1980s. Effort data (trip, days fished, or hours fished) are available with dressed weight for a few species since 1990. Red grouper, king mackerel and, possibly, cobia, appear to be the only major species with continuous annual landings and effort recorded from 1990 through 2011. The king mackerel landed in Lee and Collier counties probably were landed between Key West and the Dry Tortugas. Cobia and red grouper are better associated with the southwest Florida area, and CPUE of red grouper, in particular, might be a good indicator of habitat quality of the SWFS.

Although changes in fishery management affect landings data for certain periods, which would differ by species, annual landings data for certain species and certain periods clear of new regulatory actions could provide a view of change over time in the habitat value of the southwest coastal area. For example, landings of striped mullet from 1996 to the present and blue crab landings, possibly from the earliest records to the present, might provide good measures of estuarine habitat quality. Landings of stone crab claws might provide a good index of habitat quality of the SWFS.

The fish community in the Ten Thousand Islands has been sampled repeatedly in the past with fisheries independent sampling by otter or roller trawls, and estimates of relative abundance and density are available from some of the studies (Yokel, 1975; Carter *et al.,* 1973; Shirley *et al.,* 2005). Shirley *et al.* (2005) focused on community composition and emphasized the importance of looking at differences in community metrics. The smaller species of the lower to middle trophic levels were the principal species caught in the trawls.

Eklund (2005) proposed goliath grouper abundance as a performance measure for the reestablishment of more natural flow patterns to the Ten Thousand Islands through CERP's Picayune Strand Hydrologic Restoration Project. Because of the relationships she found between goliath grouper abundance and habitat factors, Eklund (2005) decided that the giant fish integrated the effects of habitat change that affected many other fish species. Her multiple regression model, based on four characteristics of riverine habitat, explained 92 percent of the variation in goliath grouper sampling CPUE. She noted that only when averaged over the entire sampling year and all parts of the river sampled, rather than over short stretches of space and time, was goliath grouper CPUE related to the four abiotic factors.

Sources of Change

The flow of freshwater to estuaries of the Ten Thousand Islands has been radically altered by upstream water management. The case of the estuaries downstream from Fakahatchee Strand and Picayune Strand provides a major example. Other systems that have been affected include Chokoloskee Bay, affected by channelization of the Barron River, Rookery Bay, affected by the channelization of Henderson Creek, and Naples Bay, affected by canal discharges into Gordon River. Our focus is on the system downstream from Fakahatchee and Picayune strands because of the substantial research that has centered on these areas.

Faka Union Bay, immediately west of Fakahatchee Bay, which originally received freshwater inflow from the Wood River, a small natural tributary of Picayune Strand, now receives the discharge of a major drainage canal system that originally was known as the "Golden Gate Estates" canal system. The Faka Union Canal watershed now includes Southern Golden Gate Estates (SGGE, site of the present Picayune Strand Restoration Project, located between U.S. Highway 75 and State Road 41) and part of Northern Golden Gate Estates (NGGE), which lies north of U.S. Highway 75.

The total watershed directly affected by the canal system originally encompassed an area of about 234 square miles (606 square kilometers) (Black, Crow, and Eidsness, Inc., 1974, cited in the SGGE Conceptual Plan 1996, also Wang and Browder, 1986). Another estimate, 189 square miles (490 square kilometers), was given in the Hydrologic Restoration of SGGE Conceptual Plan, South Florida Water Management District (1996) and SGGE Project

Management Plan (USACE/SFWMD, 2001) and SGGE Environmental Assessment (USACE/SFWMD, 2001). The Gordon River, which discharges into Naples Bay, is the other outlet of this extensive canal system.

The Gulf American Corporation (GAC) began construction of the roads and canals in the 1960s and completed the system, consisting of 279 miles of roads and 48 miles of canals, in the early 1970s. The canal system consists primarily of four north-south aligned major canals: Miller Canal, Merritt Canal, Faka Union Canal, and Prairie Creek Canal. The other three canals join Faka Union Canal in the southern part of Picayune Strand, north of State Road 41. Faka Union Canal continues south to discharge across a fixed weir immediately north of the Tamiami Canal at State Road 41. The Faka Union Canal continues south under State Road 41 to discharge directly into Faka Union Bay. The Faka Union Canal directly interrupted flow to the Wood River. By lowering the groundwater in the vicinity, it also affected flows to rivers east and west of Faka Union Canal.

Management of the canal during and after the GAC went bankrupt in 1978 determined the extent to which the canal system affected the hydrology of the area. After GAC left the area, the canal system was first managed by Collier County and then by the Big Cypress Basin Board of the South Florida Water Management District. The departure of water levels in Prairie Creek Canal, the easternmost canal in the system, from water levels in a well 2.5 miles east into Fakahatchee Strand (distant site) was used by Starnes and Duever (2011) to describe four hydrologic periods since 1987, when water level recorders were placed in wells along a transect running east from Prairie Creek Canal across Fakahatchee Strand. Plotted departures in water level illustrate how changes in the management of the canal system were reflected in water levels. The first period, 1987 to 1992, when there was a lack of weed management in the canals, may have captured conditions for much of the previous 20 years; it showed wide seasonal fluctuations (i.e., wet season-dry season) in water level differences between the two points. During 1983 to 1997, aquatic weed control in the canals stabilized extreme departures in water levels between the two points. Then, from about 1998 to 2003, a control structure was added to Prairie Creek Canal and wide fluctuations in departures between water levels returned. Finally, beginning about 2005,when Prairie Creek Canal was plugged in the first phase of the Picayune Hydrologic Restoration Project, the water levels in the canal departed less from the distant site and even matched it during some wet seasons, when water levels at both sites were above land surface.

Changes in Freshwater Flow to Downstream Bays

The quantity, timing, and distribution of freshwater inflow to the bay systems of the Ten Thousand Islands were changed substantially by the canal system. The canal system greatly increases the inflow of freshwater into Faka Union Bay during the wet season, decreases dry season flow, and increases the number of dry season days without any flow. The transition between wet season flow and dry season flow became more abrupt, and the natural seasonal difference in flows was accentuated. The canal system also affected other bays. It diverted surface and groundwater flow from Fakahatchee Bay, which lies directly east of Faka Union Bay and downstream from Fakahatchee Strand. The diversion reduced both wet season and dry season flow to the larger bay, although Fakahatchee Bay was influenced by low-salinity water entering from Faka Union Bay through a direct connection between the two bays. The canal system and associated road system also diverted surface and groundwater away from the small rivers and bays immediately west of Faka Union Bay, including Pumpkin River and Pumpkin Bay.

Popowski *et al.* (2004) provide the following summary. Faka Union Canal discharge records measured at the gauging station located upstream from the outfall weir are available starting in 1969. The average discharges for the period of record are 115 cubic feet per second (cfs) during the dry season (November through May) and 460 cfs during the wet season (June through October) (South Florida Water Management District, 1996). An extreme discharge of 3,200 cfs occurred shortly after the canals were built. Flows exceeding 2000 cfs occurred more recently (i.e., 1995 and 1999) (data from A. Nath, Big Cypress Basin Board).

Pressures Linked to Changes

Freshwater inflow affects many environmental conditions in the downstream estuary (Figure 1). It establishes salinity gradients, temperature gradients, and gradients in turbidity and nutrients. Furthermore, it affects both vertical and horizontal circulation, which affect, among other things,

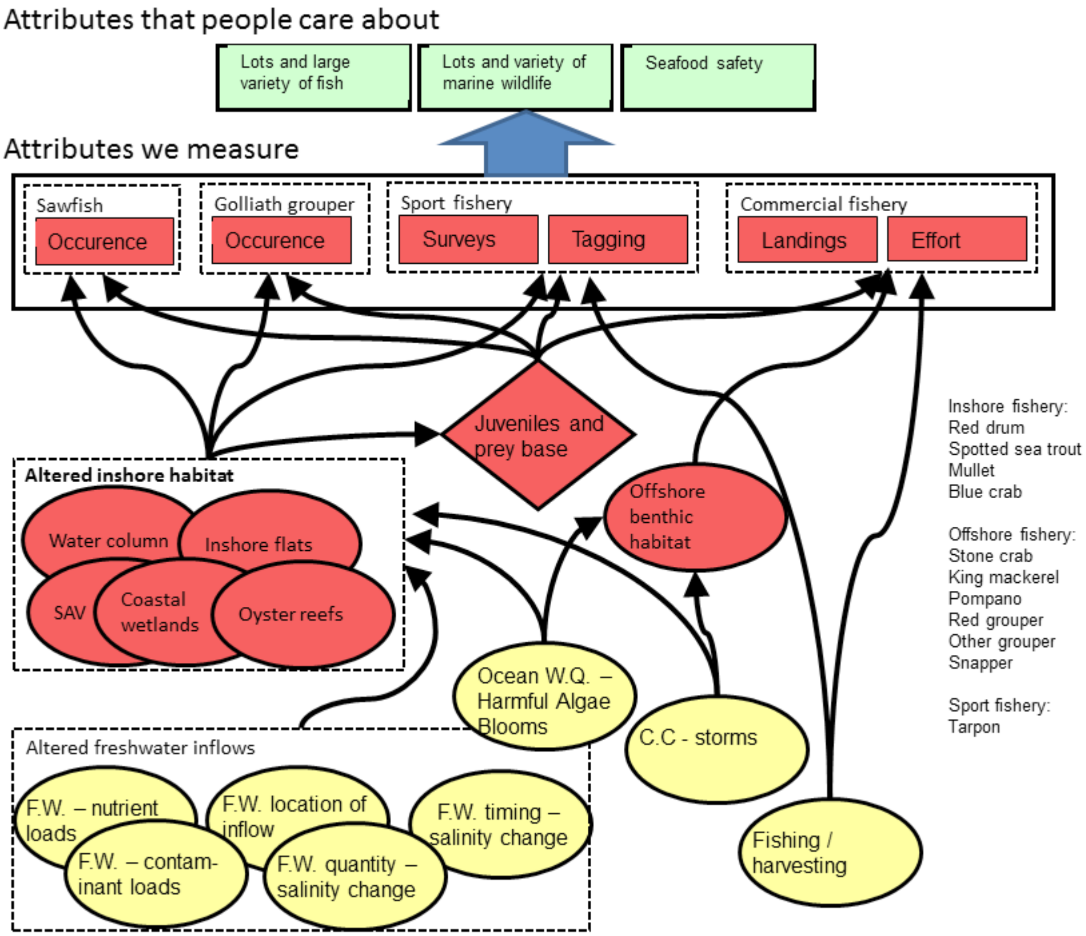

Figure 1. Fish and shellfish submodel diagram for the Southwest Florida Shelf subregion.

particle (and ichthyoplankton) transport and concentrations of dissolved gases, especially oxygen.

Since salinity and circulation are features of estuarine animal habitat, the habitat of fish, crabs, and shrimp was changed. Studies of changes in both faunal habitat and the fauna have focused on comparing Faka Union Bay with other nearby bays thought to have been less impacted by the canal system than Faka Union Bay, which receives the direct discharge of the canal system. While it has become clear that these other bays also have been impacted, the comparisons are still useful.

Most studies of the biological effects of changes in freshwater inflow in the Ten Thousand Islands have focused on the effect on fishes of changes in salinity patterns. Salinity is one dynamic dimension of fish habitat. Dissolved oxygen is another dynamic dimension. Relatively fixed features that determine fish habitat include bottom contours, bottom vegetation, shoreline configuration, and shoreline vegetation. Optimum habitat for any one species occurs where favorable salinity and favorable bottom or shoreline features overlap. Ideally, the salinity gradient provides favorable habitat somewhere in the estuary for a spectrum of fauna with different salinity requirements. Changes in freshwater inflow from the natural pattern can shift salinity zones to areas of less than favorable bottom or shoreline habitat and constrict salinity zones so that fewer species and fewer individuals within species can be accommodated with the salinity they need (Browder and Moore, 1981).

Changes in Salinity

Examination of three years of 30-min-interval salinity data for Faka Union Bay and a reference site in Fakahatchee Bay/

Fakahatchee River collected by the Rookery Bay Natural Estuarine Research Reserve indicates both spatial and temporal changes in salinity patterns as a result of changes in freshwater inflow regimes (Popowski *et al.,* 2004). Shirley *et al.* (2005) summarized salinity data from faunal studies conducted over several decades (early 1970s, early 1980s, and early 2000s) and noted that salinity in Faka Union Bay was, on average, 6-10 units lower than salinity in the other bays during the three periods.

Wang and Browder (1985, 1986) developed a hydrodynamic model of Faka Union and Fakahatchee bays that showed qualitatively and quantitatively how salinity zones shifted and zonal areas changed as a function of magnitude of freshwater inflow. Faunal models based on data from Browder *et al.* (1986) were used to show the effect on faunal abundance of changes in salinity-band area under different freshwater inflows (Browder and Wang, 1987). In a later study, Wang and Browder (2004) used their hydrodynamic model and updated faunal models from their earlier work to show that faunal abundance was substantially higher under freshwater flow regimes mimicking the natural pattern. The natural pattern for the same period was approximated by a natural-system version of the hydrologic model used to approximate the hydrologic function of the area (MIKE SHE hydrological model, as described in USACE/SFWMD, 2004). In model simulations, the "Tentatively Selected Plan" for the Picayune Hydrologic Restoration Project showed high faunal abundance similar to that of the natural system.

Both Eklund (2005) and Shirley *et al.* (2005) quantified salinity variation in their work, proposing that the rate of change in salinity rather than salinity, per se, was an important factor influencing fish well-being and abundance. In a regression relationship with goliath grouper sampling CPUE, Eklund (2005) found that salinity change was one of four factors explaining variation in CPUE. The more important factors were bathymetric complexity, proportion of the shoreline eroded, and proportion of measured time that dissolved oxygen concentration was less than 2 ppm.

Changes in Dissolved Oxygen Concentrations

Eklund (2005) found that the waterways she sampled differed in the percent of time that measured dissolved oxygen concentrations were below 2 ppm. The upper parts of the Pumpkin and Wood rivers always had minimum dissolved oxygen concentrations less than 0.35 ppm, and their middle sections had minimum dissolved oxygen concentrations less than 1, except toward the end of the wet season. Not only was grouper CPUE negatively correlated with the period of measured time that conditions were anoxic, but also crabs and catfish caught in sampling traps in the rivers with the greatest percent of time anoxic were always dead. Noting the disparity in goliath grouper CPUE among the six natural flow-ways, Eklund (2005) concluded that the rivers that were connected to upstream water sources were the productive ones because freshwater flow provided circulation that reduced the frequency and duration of anoxic events.

Changes in Physical Habitat

Changes in the freshwater inputs to the many small bays of Ten Thousand Islands led to changes in physical features of the rivers and estuaries. Eklund (2005), examining habitat factors that influenced the abundance of goliath grouper in six small rivers and three canals of the Ten Thousand Islands, documented differences in habitat structure among waterways. Some had substantial bathymetric variation compared to others, and some had a high proportion of shoreline that was eroded away below the surface, creating an overhang. Canals and small rivers did not separate cleanly based on these differences. In fact, one canal, which she referred to as 92 East (based on its relation to State Road 92), had the second highest proportion of eroded shoreline, 59 percent (second only to Little Wood River, 70 percent), whereas some of the creeks had almost none. While all of the canals had relatively flat bathymetry, a few of the rivers did also. Loss of freshwater flow from their headwaters due to construction of the Faka Union canal system may have prevented bank erosion in some of the small rivers, making them less suitable goliath grouper habitat. Faka Union Canal was poor grouper habitat on three counts—high salinity variability, lack of eroded shoreline, and lack of bathymetric complexity—but had good dissolved oxygen concentrations because of its freshwater inflow.

The eroded banks of mangrove shorelines provide prized habitat for many species. Large numbers of goliath grouper, gag grouper, snook, and gray snapper have been seen in these overhangs (Eklund, 2005). Rocky depressions provide another type of habitat for these species. The overhangs, in particular, are rich with small fish and other small prey

(Eklund, 2005). Therefore, an absence of such features may reduce the abundance of other fauna in addition to goliath grouper.

Changes in Bottom Vegetation

SAV may be a component of another part of this overall report; however, it is mentioned here because it is an important aspect of fish habitat and because observations were available from fish studies. Observations from several faunal studies (Carter *et al.,* 1973; Yokel, 1975; Browder *et al.,* 1986) suggest that the seagrass cover in Faka Union Bay and other nearby bays declined substantially since the early 1970s post Faka Union Canal construction. Based on quantitative information in Carter *et al.* (1973), we calculate that SAV average dry weight in about 1972 measured 44.61 kg/ha in Faka Union Bay, compared to 51 kg/ha in Fakahatchee Bay. Yokel (1975) also found substantial amounts of seagrass in Fakahatchee Bay. However, Browder *et al.* (1986), conducting trawl sampling in the area 10 years later, found little seagrass in either Faka Union or Fakahatchee bays. Their qualitative analysis of the associated seagrass bycatch in trawl collections suggested there was more seagrass in Pumpkin Bay than the other two bays. Colby *et al.* (1985) reported no seagrass bycatch in 97 percent of their trawl collections in nine bays of the Ten Thousand Islands, including Faka Union and Fakahatchee. According to Popowski *et al.* (2004), seagrasses associated with open water habitat are not extensive in the Faka Union Bay region but are locally abundant in the shallow waters off the outermost islands along the Gulf edge of the Ten Thousand Islands. Seagrass beds are extensive in the shallow water of Gullivan Bay south of Cape Romano. Popowski *et al.* (2004) surmised that "frequent freshets and long periods of extreme low salinity may have contributed to loss of seagrass in Faka Union and Fakahatchee bays."

Change in Oyster Reef Habitat

Intertidal and submerged oyster reefs form another type of bottom habitat important to fish, crabs, and shrimp, many of which settle out of the plankton onto the reef at early life stages. The Ten Thousand Islands have an extensive amount of oyster reefs. Over 300 macrofauna species can live in or associated with oyster beds, and over 40 species may live in a single oyster bed (Wells, 1961).

Small crabs and shrimp of many species live in the crevices between oyster shells. The skillet fish (*Gobiesox strumosus*), which was abundant in ichthyoplankton catches but rarely caught in trawls (Browder *et al.,* 1986, 1988) is an oyster reef associate. Red drum, an important sport fish species in the Ten Thousand Islands, is a commonly recognized inhabitat of oyster reef areas.

Change in Area of Overlap of Favorable Physical and Dynamic Habitat Features

The overlap of favorable salinities with favorable structural features creates the optimum habitat for a given species (Browder and Moore, 1981) or, in some cases, a given life stage within a species. Freshwater inflow provides a salinity range in which favorable salinities overlap with beneficial structural habitat to create optimal habitat for a number of species.

Favorable habitat relates not only to the salinity at any given place and time but also to the rate of change in salinity from one place to another (which affects habitat area) and one time to another, which affects the ability of the organism to maintain osmotic stability (e.g., Serafy *et al.,* 1997, regarding fish). Eklund (2005) found that, in general, canals had higher rates of salinity change than creeks and rivers, but there were exceptions. For example, 92 Canal East had a rate of change more typical of creeks and rivers, whereas Blackwater River and Royal Palm River had relatively high rates of salinity change.

Dissolved oxygen concentrations represent another dynamic dimension of faunal habitat. Eklund (2005) found that dissolved oxygen concentrations on the annual and river scale affected goliath grouper sampling CPUE and size. Dissolved oxygen concentrations at the time and place where sampling traps were set killed species such as crabs and catfish that were caught.

Status and Trends: Changes in Fish, Shrimp, and Crabs

Fishery statistics can reflect changes in the quality of fishery habitat. Several indicators based on fisheries were proposed in the Attributes We Can Measure section. Figures 2 and 3 show the CPUE of the red grouper handline fishery from 1990 through 2011 and Lee County stone crab landings and value from 1962 to 2011.

There are no before-canal studies of Faka Union Bay; however, several investigators have compared fish communities in Faka Union Bay and nearby less-impacted bays to approximate the difference between pre- and post-drainage Faka Union Bay fish communities. The results of the studies agreed that relative abundance of fish, shrimp, and crabs in Faka Union Bay was lower overall than in comparative systems. Carter *et al.* (1973) found that the abundance of trawl-caught fish was greater in Fakahatchee Bay than in Faka Union Bay. Browder *et al.* (1986) found that five of the 10 dominant trawl-caught fish species were significantly more abundant in Pumpkin Bay than in Faka Union Bay, and four of these 10 species were significantly more abundant in Pumpkin Bay than in Fakahatchee Bay. The six dominant trawl-caught macroinvertebrate species (including pink shrimp and blue crab) differed in abundance even more markedly between Faka Union Bay and one or both of the other two bays. Colby *et al.* (1985), in a comparison of forage fish communities in Faka Union Bay (Strata I) to that of eight nearby bays to the east (Strata II) and the west (Strata III), found that relative fish densities were lower in Faka Union Bay than in comparable habitats in the other bays in 11 out of 12 cases. Furthermore, they noted that, with the onset of the rainy season, fish densities declined and the decline was greatest in Faka Union Bay (83 percent, versus 70 percent, and 50 percent).

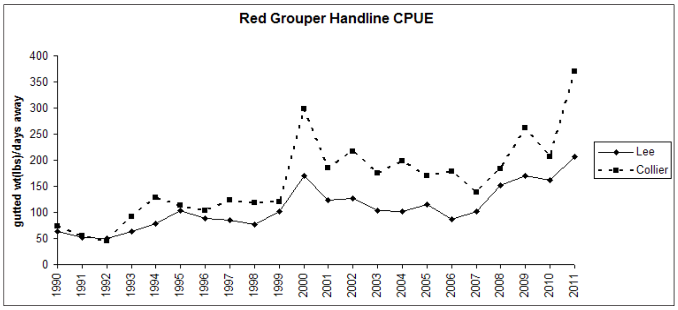

Figure 2. Long-term trend in red grouper catch per unit effort in Lee and Collier counties.

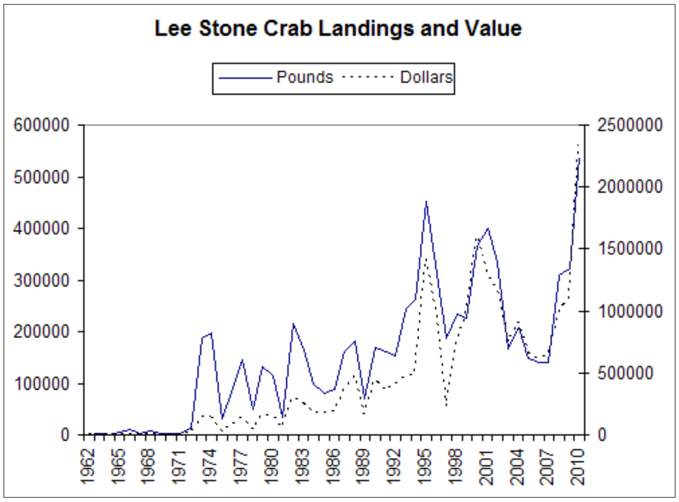

Figure 3. Long-term trend in stone crab landings in Lee and Collier counties.

Shirley *et al.* (2005) summarized the fish species caught in earlier studies, noting that Carter *et al.* (1973) employed seines, surface trawls, and otter trawls, and both surface and otter trawls were used by Colby *et al.* (1985) and Browder *et al.* (1986). Fish species listed as dominants in one or more of these studies included bay anchovy (*Anchoa mitchilli*), pinfish (*Lagodon rhomboides*), silver jenny (*Eucinostomus gula*), pigfish (*Orthopristis chrysoptera*), silver perch (*Bairdiella chrysoura*), yellowfin menhaden (*Brevoortia smithi*), and scaled sardine (*Harengula jaguana*). Use of seines and surface trawls led to the greater number of species ordinarily found in the upper water column rather than demersally (e.g., bay anchovy, yellowfin menhaden).

Based on ordination analysis, Colby *et al.* (1985) concluded that most of the dominant species had salinity optima at intermediate to high salinities rather than low salinities. Colby *et al.* (1985) decided that salinity was not the only factor that depressed fish abundance in Faka Union Bay because fish abundance was lower there in May 1983 when salinities were comparable in all estuaries. Perhaps changes in bottom vegetation were responsible for the differences.

Both Browder *et al.* (1986) and Colby *et al.* (1985) commented that Faka Union Bay did not have a unique fish community but only lower densities of the same species found in the other bays. Apparently, when the habitat of these species in Faka Union Bay became more constricted, they did not disappear to be replaced by other species as the dominants—fish abundance simply declined overall.

Shirley *et al.* (2005) noted that the previous studies had focused on determining differences in abundance rather than differences in community structure. Shirley *et al.* (2005) used multivariate analysis techniques to explore differences in community characteristics between Fakahatchee Bay, considered to be the reference estuary, and the two disturbed estuaries, Faka Union Bay and Henderson Creek. They divided the study period into eight segments: early dry, late dry, early wet, and late wet in each year. Based on an analysis of similarities, they concluded that Fakahatchee Bay species composition was significantly different from species composition in the other two estuaries during all seasons except the late wet season. Overall, in one season or another, 34 unique species contributed most to the species composition differences between the reference estuary and the estuaries with altered freshwater inflow. More than 75 percent of these species were in greater abundance in the reference estuary, Fakahatchee Bay. Carter *et al.* (1973) found a greater diversity, as well as a greater abundance of fish, in Fakahatchee Bay compared to Faka Union Bay.

The changes in freshwater flow to the estuaries of the Ten Thousand Islands may have affected gamefish species, as typified by snook. Carter *et al.* (1973) found that tidal streams were a major nursery area for young snook. Shallow brackish stream habitats provided young snook with an abundant supply of small forage organisms, flowing water, low salinities, favorable water temperatures, and a general absence of larger piscivorous predators. Presumably, habitat for young snook would shrink where the flow of freshwater is diverted from creeks to canals. Any diminishment of principal prey species might also affect young snook.

Topics of Scientific Debate and Uncertainty

Uncertainty exists about the effects of Picayune Hydrologic Restoration on estuaries, despite studies suggesting negative effects of the canal system on not only Faka Union Bay but all the other bays in the area, including Fakahatchee Bay to the east and bays from Pumpkin Bay to Royal Palm Bay to the west.

Uncertainty exists over the effect of hydrologic restoration of Picayune Strand on the future invasions of downstream estuaries by Mayan cichlids, lionfish, and other invasive exotic species.

Acknowledgments

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Habitats: Inshore Flats

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In a nutshell

- Subtidal and intertidal sand and mud flats serve as habitat to a diverse assemblage of infaunal and epifaunal organisms and provide shoreline protection against erosion and storms, sustenance through food web connections to foraging birds and finfishes, and carbon sequestration and organic degradation.
- Through these connections, inshore flats help to support commercial and sport fisheries, preserve endangered species, provide shoreline protection, and contribute to the aesthetics of the coast.
- The drivers with greatest significance to the coast are climate change, water management, and coastal development.
- Altered freshwater inflow is the most serious and immediate pressure requiring attention along the SWFS.

Four habitat types are recognized for the Inshore Flats submodel: (1) siliciclastic or carbonate subtidal mud flats (subtidal soft bottom); (2) siliciclastic subtidal sand/mud flats (subtidal firm bottom); (3) intertidal tidal deltas (intertidal firm bottom); and (4) intertidal sand shoreline fringe (intertidal firm bottom). All four habitat types are found among the four geomorphologic provinces: Barrier Islands, Ten Thousand Islands, Everglades, and Cape Sable. Subtidal flats composed of sand and mud or mud are ubiquitous throughout the system. The distribution of intertidal deltas varies, however. Tidal deltas tend to be large and most active within the Barrier Islands Province. Here, inlets between barrier islands experience swift tidal currents, and the coast's position relative to Gulf-crossing tropical storms mobilizes and deposits deltaic sediments with greatest frequency. The Everglades Province has narrow rivers separating the inner bays from the open coast; strong tidal currents through these channels generate large deltas. Tidal deltas exist within the outer and inner bays of the Ten Thousand Islands, but the more open construction of the coast less effectively focuses tidal currents to generate large deltas. Finally, Whitewater and Oyster bays, located within the Cape Sable Province, are almost completely isolated from open water. Tidal deltas here are inconsequential. Intertidal shoreline fringe is found in all four provinces, but fringe is best developed in the Barrier Islands and Ten Thousand Islands provinces where accommodation area on the backside of islands is great.

Inshore flats are defined as flat bottom, sub- or intertidal habitats that lack an epifaunal oyster or seagrass community and are located inside the outer coastal margin. The two most significant environmental characteristics that control a flat's infauna and epifauna are: the height of the substrate relative to mean sea level and the sedimentary consistency of the substrate. The position relative to mean sea level dictates whether the habitat is emergent in air for part of a tidal cycle (i.e., intertidal) or how deep within the subtidal zone the benthos sits. This latter characteristic controls other physical water quality measures, like dissolved oxygen and the frequency and duration of hypoxia events, and ambient light level, which is affected by depth of light penetration. Firmness of the substrate affects the capacity to support an epifauna—preventing the sinking of an organism in the substrate—and the burrowing behavior of the infauna. Substrates that consist of sand and sand mixed with mud (mud is an admixture of clay- and silt-sized particles) tend to be firm, supporting an epifauna, and typically have high sediment porosity and permeability leading to well oxygenated interstitial fluids that can support a diverse and deeply penetrating infauna. Muds may be incompetent and not support a shelly epifauna (De Deckere *et al.,* 2001) and often have low porosity and permeability, prohibiting the existence of an extensive infauna (Sanders, 1958; Rhoads and Morse, 1971; Rhoads and Germano, 1982).

The composition of the sediment can vary. Sand-sized material is most commonly composed of quartz that is either derived from offshore-longshore drift, which is then moved landward due to storm and tidal activity (Tanner *et al.,* 1963; Perlmutter, 1982; Davis *et al.,* 1993) or, less commonly, from downstream transport from the watershed. Less commonly, the coarser sediment is composed of calcium carbonate shell fragments (Scholl, 1963; Sussko, 1989). Mud may be composed of phyllosilicate clays, carbonate, or finely disseminated organics. Phyllosilicates are the rarest of the three and are derived from upstream in the watershed as weathering products of silicate minerals within older sediments or sedimentary rocks. Carbonate mud is biogenically produced either in the estuary itself, in marine sediments that are transported upstream by storms or tides, or in freshwater and brackish water marshes (marls produced by algal and microbial communities; Browder *et al.,* 1991; Merz, 1992) that are moved to the estuary by sheet or channel flow. Finally, organics can be derived in situ or be transported in from upstream. Intertidal flats are invariably dominated by quartz sand-sized grains. Wave influences, regardless of the limited fetch in inshore settings, are energetic enough to prohibit the deposition of mud-sized grains.

The distinguishing characteristics that define inshore flat habitat types are relative water depth with respect to mean sea level and the sedimentary substrate composition: habitats may be subtidal or intertidal; subtidal substrates may be composed of sand and mud or mud; and intertidal substrates are composed of sand. Additionally, intertidal sand flats occur as one of two varieties that are distinguished by the relative stability and residence time of the sands. Storm tidal deltas form on the inside edges of the outer and inner bays landward of tidal inlets. During storm flood, tides sands are transported landward and deposited on these deltas. (Ebb flood deltas may also occur seaward but tend to be ephemeral, as the sands deposited in these features are quickly remobilized and transported away; see Reinson [1979] for general description of tidal deltas.) Consequently, storm tidal deltas remain stable between storm and extreme tidal events. Intertidal sand flats also occur as beach aprons on the bayside of islands. These structures are influenced by waves and by tidal cycle fluctuations.

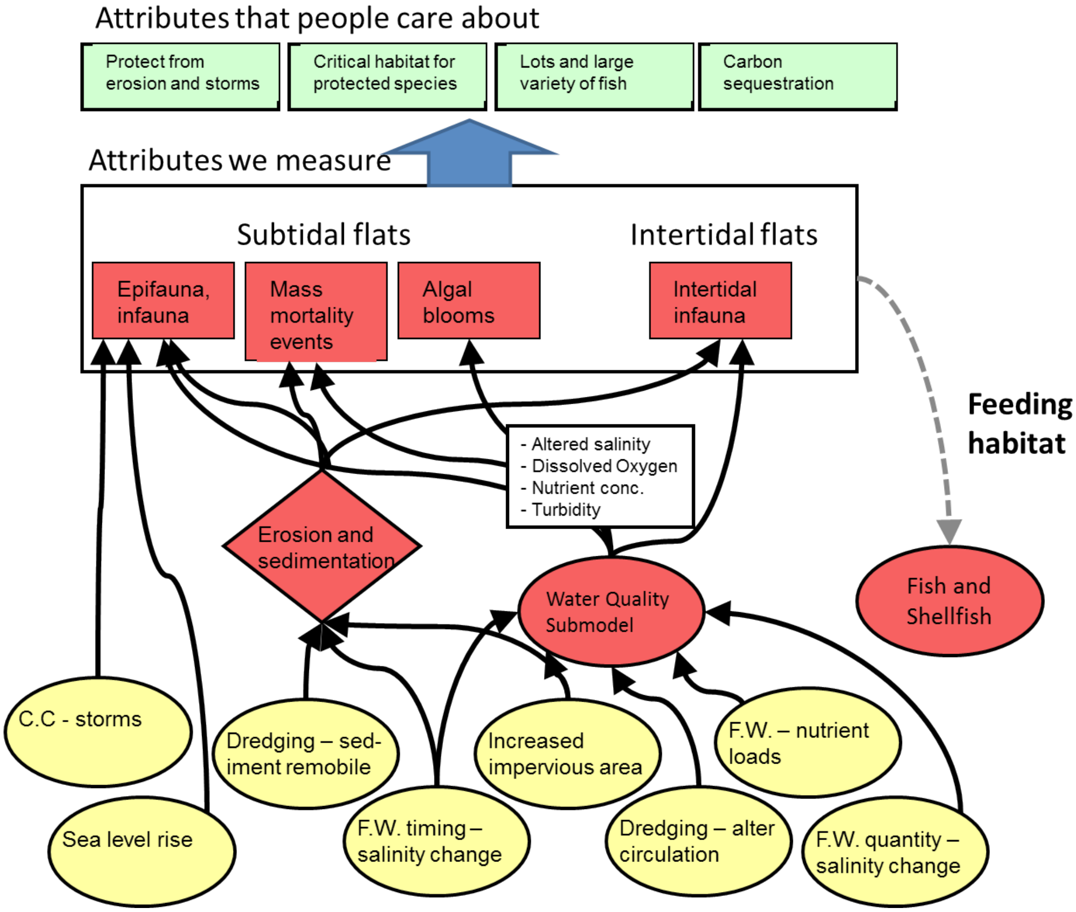
Attributes People Care About

Critical Habitat for Protected Species

Intertidal mudflats are highly productive ecosystems that are often poorly acknowledged (Erftemeijer and Lewis, 1999; Dittman, 2002). Infaunas and epifaunas have been described for a number of regions in Florida and the eastern Gulf of Mexico coast (Lyons and Collard, 1974; Culter, 1988; Posey *et al.,* 1998; Brooks *et al.,* 2004, 2006). Intertidal flats serve as habitat for foraging wading birds, and many of these are protected or listed species (Quammen, 1984; Ogden, 1994; Erwin, 1996). Exposed mud and sand flats provide sustenance from the available infauna and epifaunal invertebrates; invertebrate densities can exceed 10,000 individuals per m2 (Barnes *et al.,* 1997). Intertidal, when submerged, and subtidal flats serve as critical grazing and predation habitat for finfish, many of which are protected.

Abundance and Large Variety of Fish

Similarly, inshore flats serve as feeding habitat for a large variety of fish species, regardless of their protected status. Many of these fish species are benthic feeders and prey upon epifaunal invertebrates. Sand and muddy substrates in southwest Florida support a diverse invertebrate infauna (Hooks *et al.,* 1976; Phillips *et al.,* 1990; Dawes *et al.,* 1995). Certain fish (e.g., skates and rays) are specialized to feed on shallow burrowing invertebrates (Howard *et al.,* 1977; Smith and Merriner, 1985).



Inshore flats submodel diagram for the Southwest Florida Shelf.

Protection from Erosion and Storms

Intertidal flats are commonly found adjacent to the leeward shorelines of barrier and outer coastal islands. Depth gradients are often slight, thereby creating a wide protective shallow fringe to an island's lee shoreline. Though storm erosion is typically more impactful on an island's windward face, tidal surge and wave fetch can be great on the backside. The intertidal flats, therefore, do provide an erosion buffer for back-barrier wetlands. Additionally, mangrove forests commonly prograde onto adjacent intertidal flats, making these paralic environments important buffers for mangrove forest development (Alongi, 2008).

Carbon Sequestration (Burial of Organic Carbon)

Inshore flat sediments, particularly those dominated by muds, are typically rich in organic carbon. Organics settle from suspension either independently or attached to clay-size detrital sediments, accumulate on the estuarine seafloor, and can be quickly buried (Bridgham *et al.,*2006; Howe *et al.,* 2009; Sanders *et al.,* 2010). Because sediments are rarely well oxygenated below a few centimeters of the substrate, these organics have greater likelihood of becoming buried. Over geologic time during intervals of relative sea-level rise, shorelines transgress and organic-rich muds remain buried, increasing the likelihood of long-term carbon storage.

Drivers and Pressures

Of the lengthy list of drivers affecting southwest Florida, those of greatest significance for inshore flats are: (1) climate change; (2) water management practices; and (3) urban development. Climate influences manifest themselves as ecosystem pressures from changes in storm intensity and frequency and from sea-level rise. Water management practices generate pressures associated with the changes in the quantity and timing of delivery of freshwater, and in the delivery of nutrients. Finally, urban development influences hydrology by increasing impervious area on land and through channel dredging in the estuaries. Each of these pressures will be considered separately.

Climate Change – Storms

One of the predictions of global warming is an increase in intensity and perhaps frequency of tropical storms (Webster *et al.,*2005; Oouchi *et al.,* 2006). Hurricanes generate extreme tidal surges and deepen wavebase; this influences the transport, deposition, and erosion of sediment. Storm deltas are activated; overwash can occur on barrier islands to build overwash fans, thereby affecting the back-barrier marshes and aprons (e.g., Donnelly *et al.,* 2004; Wang and Horwitz, 2007); and mangrove fringe forests can be back-stepped through erosion to enlarge inner and outer bays to create new subtidal mud and sand flats (e.g., Risi *et al.,* 1995; Baldwin *et al.,* 2001). Because flood storm tides are typically more energetic than ebb storm tides, traction- and suspended-transported sediments are redistributed with net transport shoreward. Coarser materials (sand and shell gravels) are moved inshore, while muds, which are capable of remaining in suspension during less-energetic flows, are transported and eventually deposited offshore (Davis *et al.,* 1989). Consequently, storm tidal deltas of the inner and outer bays tend to build, and muds are deposited on the broad shelf of the Gulf of Mexico and Gullivan Bay.

Sea-Level Rise

Sea-level rise influences the coast through two mechanisms. The net effect of the combined rates of sea-level rise and sedimentation influence coastal geomorphology (see “Physical Setting: Dynamic Geomorphology” section, page 8), and sea-level rise alters the distribution of salinities within the estuaries and, therefore, the position of the salinity gradient and ecotones.

Over decadal and centennial time scales, the high rate of sea-level rise relative to the rate of sedimentation will eventually cause an environment to become deeper. Intertidal flats may become subtidal; subtidal flats may deepen and experience lower ambient light levels and greater frequencies or intensities of hypoxia. With deepening comes a concomitant change in sedimentary character, with substrates becoming finer grained and more mud-rich. Oyster reefs become less productive with increasing subtidal depth and can effectively “drown” and disappear; such phenomena have been documented in Holocene sediment cores (Bratton *et al.,* 2003; Wohlpart *et al.,* 2007). Mangrove-forested islands can also drown when the rate of sea-level rise exceeds the rate of production (Ellison and Stoddart, 1991).

Shifts in salinity affect an organism’s abilities to osmoregulate and can cause physiologic stress and mortality. Changes in the salinity gradient due to sea-level rise not only shift the biogeographic distribution of organisms, but may also place appropriate salinities in what is otherwise a less hospitable habitat due to other environmental conditions. For example, the incursion of higher salinity water within estuaries of the Ten Thousand Islands has placed the most productive waters for oyster growth and reproduction within the river channels, rather than the inner bays. River channels have much less accommodation space for oyster reef development than inner bays, and river channel substrates are generally too mobile to permit oyster settlement and survival (Savarese ane Volety, 2001; Savarese *et al.,* 2003).

Altered Freshwater Inflow – Quantity and Timing

The alteration of freshwater inflow due to water management practices is perhaps the most serious and immediate pressure requiring attention along the SWFS. Freshwater is over-discharged into some estuaries (e.g., Faka Union Bay in the Ten Thousand Islands [US ACOE, 2004]; Caloosahatchee River in the Barrier Islands Province [Chamberlain and Doering, 1998]); the magnitude of freshwater releases can be extreme, causing freshets that can unduly stress faunas and floras (Doering *et al.,* 2002; Barnes, 2005). In other estuaries, freshwater sheetflow is interrupted because of drainage canal networks that redirect freshwater to one bay. This phenomenon has been particularly devastating to the bays west of Faka Union Bay in the Ten Thousand Islands which, as a result, have anomalously high salinities (Savarese and Volety, 2001; Savarese *et al.,* 2003; Tolley *et al.,* 2005). The timing of freshwater delivery is also of importance. Freshets during times of spawning or larval recruitment can obviate an entire year’s reproductive effort.

Increases in freshwater delivery to the estuary can also affect sedimentation rate. The suspended sediment load is amplified when freshwater flow increases. If the suspended load becomes extreme, benthic communities can become smothered and mass mortality can occur.

Channel Dredging – Altered Circulation and Sediment Remobilization

The dredging and maintenance of channels effectively reduces tidal friction, thereby allowing easier transport of marine and freshwater during tidal cycles and times of freshwater runoff (Bray, 2008). Consequently, channels further influence the quantity and timing of freshwater delivery, which can alter the distribution of salinities in the estuary. Swifter tidal flows are more competent and carry greater sediment loads. This may alter the deposition and erosion of sediments on inshore flats.

Increased Impervious Area

An increase in the impervious area of a watershed effectively increases runoff and the delivery of freshwater to an estuary which, in turn, can increase the sediment load. Pervious surfaces, alternatively, promote groundwater recharge and reduce the volume of runoff (Arnold and Gibbons, 1996).

Altered Freshwater Inflow – Nutrients

Freshwater can become enriched in nutrients by the excessive use of fertilizers within a watershed. The resulting principal effects can be numerous. Eutrophication can lead to algal blooms which may further result in decreased concentrations of dissolved oxygen, hypoxia, and anoxia events both in the water column and within the benthic pore waters, and a reduction in light transmission to the substrate (Heisler *et al.,* 2008; Anderson *et al.,* 2008).

Attributes We Can Measure

The taxonomic diversity and abundance of species are appropriate measures for the monitoring of ecosystem services of subtidal sand and mud flats. Unfortunately, these are monitoring efforts that are rarely pursued.

Subtidal Flats

Changes in epifauna and infauna. Seasonal sampling of the infauna and epifauna, to reflect wet and dry season variability, of a collection of flats spanning an estuary's salinity gradient should be used to monitor the productivity of this habitat type over time as other studies have demonstrated that significant intra-annual variability can exist (Trueblood *et al.,* 1994; Shen *et al.,* 2006). A variety of benthic indices has been established whose effectiveness has been established (Borja *et al.,* 2008). A biologist with expertise in invertebrate zoology and ecology and with a familiarity with the local fauna and field sampling methodology would be required.

Monitoring mass mortality events. The frequency and intensity of mass mortality events is symptomatic of more influential regional drivers of ecosystem change. Mass mortality is most often caused by hypoxia events, and these are most often related to harmful algal blooms. Mass mortality of epifauna is more readily observed; regular monitoring visits to a subtidal flat will reveal extensive die-offs. Infaunal mass mortality is more fleeting, however. Nonetheless, by undertaking a life versus death assemblage comparison of infauna (Kidwell, 2007; Agobian, 2010), in association with the regular monitoring described above, events that devastate an infauna can be observed (no life assemblage present in an infaunal sample).

Monitoring algal blooms. The monitoring of harmful algal blooms and their geographic and temporal patterns should be a component of the management of all southwest Florida's estuaries. Practices for measuring this attribute are found among the other ICEM submodels.

Intertidal Flats

Changes in infauna. Procedures and expertise required to monitor the infauna on intertidal flats (i.e., epifauna on intertidally exposed flats is ephemeral) are identical to what is needed for subtidal flats.

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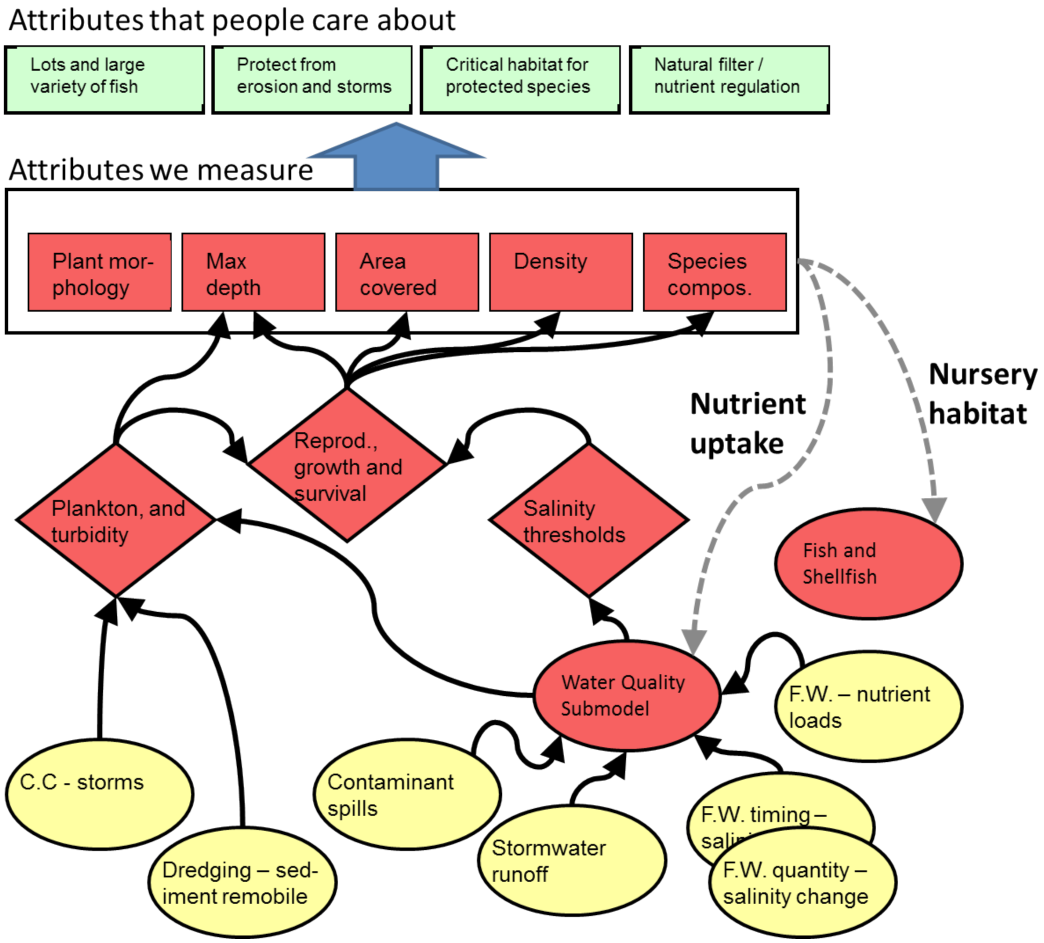
Habitat: Submerged Aquatic Vegetation

Patricia K.Goodman
Florida Gulf Coast University

In a nutshell

- Summary statements go here.



Submerged aquatic vegetation submodel diagram for the Southwest Florida Shelf.

Habitat: Oyster Reefs

Aswani K. Volety
Florida Gulf Coast University

In a nutshell:

- Oyster reefs provide a habitat for over 300 species, including fish and invertebrates, and play a major role in improving water quality and clarity via their filtration capacity, thereby removing phytoplankton, detritus, contaminants, and bacteria.
- People value oyster reefs as a place to find a large number and variety of fish. Oyster reefs stabilize sediments, protect against boat wakes, and provide a critical habitat for larval stages of fish and crustaceans. They also play a role as sentinels in contaminant monitoring.
- The damage to reefs from overharvesting, dredging, sedimentation, and altered freshwater inflows into the estuarine system can lead to a complete loss of oyster reefs in heavily-affected areas.
- Watershed alteration resulting from increasing human development and changes in salinity and contaminants has been implicated in the loss of oyster reefs in many areas of the world, including southwest Florida.

Eastern oysters, *Crassostrea virginica,* are natural components of estuaries along the eastern seaboard of the U.S., as well as the estuaries in the Gulf of Mexico, and were once abundant in the estuaries of southwest and southeast Florida (RECOVER, 2007). In the Caloosahatchee, Loxahatchee, Lake Worth, and St. Lucie estuaries (northern estuaries of the Everglades), oysters have been identified as a valued ecosystem component (Chamberlain and Doering, 1998a,b). The eastern oyster once supported a Native American subsistence fishery prior to and during early European colonization of North America (Quitmyer and Massaro, 1999) and today continues to be an important economic and ecological resource to coastal inhabitants (Ingle and Smith, 1949; Coen *et al.,* 1999; Gutierrez *et al.,* 2003). Along the southwest Florida coast, oysters exist within the estuarine and coastal areas as extensive reefs or isolated clusters or are attached to prop roots of red mangroves, often extending out at the base of mangroves (Figure 1).

The historical coastal complex of South Florida was distinctly estuarine with freshwater discharging through natural channels, as sheet flow across coastal wetlands and ground water flow, as general pore seepage, and as individual artesian springs emerging from karst pipes. As a result, conditions were favorable for the oyster to flourish and build small to extensive oyster banks and bars. In a few areas on the southwest coast, new oyster growths have shifted further inland along channels and interior bays. Oysters have an even greater temporal and spatial impact to south and southwest Florida because of the sedimentation associated with their reef development. Oyster reef development occurred along the southwest Florida coast over the last 3500 years, with reef development having a significant impact on coastal geomorphology. As reefs become emergent at low tide, they become the centers for red mangrove propagule settlement, and reefs transform into mangrove-forested islands. These islands entrap freshwater and predispose the

Figure 1. Oyster reefs beds in the Southwest Florida Shelf ecosystem.

region to estuarine conditions (Parkinson, 1989; Wohlpart, 2007). In the present day, oyster reefs are extensive along the Charlotte Harbor to the Ten Thousand Islands, with reef development decreasing southeast of Chatam River towards Everglades National Park (Savarese *et al.,* 2004; Volety *et al.,* 2009). In estuaries north of Lostman's and Broad rivers, oysters are also found on the prop-roots of red mangroves fringing the inner bays. In most of the estuaries, oyster reef coverage ranges between 5-20 acres (Volety and Savarese, 2001; Savarese *et al.,* 2004; Volety *et al.,* 2009).

Ecological Role of Oyster Reefs

Secondary Habitat and Trophic Transfer

Oysters provide habitat for other estuarine species that have significant recreational and commercial value. Grabowski and Peterson (2007) estimated that an acre of oyster reef sanctuary will result in ~$40,000 in additional value of commercial finfish and crustacean fisheries. Oysters are also ecologically important: they improve water quality by filtering particles from the water and serve as prey and habitat for many other animals (Coen *et al.,* 1999). For example, oyster reefs have been identified as essential fish habitat for resident and transient species (Breitburg, 1999; Coen *et al.,* 1999). Wells (1961) collected 303 different species that utilized oyster reefs and segregating species that used the reef primarily as shelter from those that depend on the reef for food. These organisms are then consumed by finfish and crustacean species that may be recreationally or commercially valuable (Grabowski *et al.,* 2005; Grabowski and Peterson, 2007).

Harding and Mann (2001) found that transient generalist fishes do not rely exclusively on oyster reef habitats; therefore, it may not be appropriate to identify oyster reefs as essential fish habitat for these opportunistic fishes. According to the Magnuson-Stevens Fishery Conservation and Management Act, essential fish habitat is defined as "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity" and fish is defined as "finfish, mollusks, crustaceans, and all other forms of marine animal and plant life other than marine mammals and birds" (USDOC, 1997). In general, oyster reefs provide habitat and shelter for many estuarine species (Zimmerman *et al.,* 1989; Myers and Ewel, 1990; Breitburg, 1999), especially during periods of hypoxia (Lenihan *et al.,* 2001). Harding and Mann (2001) suggested that oyster reefs may provide a higher diversity and availability of food or a greater amount of higher quality food compared to other habitats. Oyster reefs restored on mudflats have higher juvenile fish abundances compared to reefs restored in vegetated areas that could potentially cause an increase in fish productivity in an estuary (Grabowski *et al.,* 2005). The reefs can also be called essential fish habitat for oysters themselves, especially when reef height and quality and quantity of interstitial spaces for recruiting oysters are considered (Coen *et al.,* 1999). Both of these characteristics increase the recruitment, growth, and survival of oysters on reefs (Coen *et al.,* 1999).

Several species of fishes have been identified as oyster reef residents and include the naked goby (*Gobiosoma bosc*), Florida blenny (*Chasmodes saburrae*), striped blenny (*Chasmodes bosquianus*), feather blenny (*Hypsoblennius hentz*), skilletfish (*Gobiesox strumosus*), gulf toadfish (*Opsanus beta*), and oyster toadfish (*Opsanus tau*) (Zimmerman *et al.,* 1989; Wenner *et al.,* 1996; Breitburg, 1999; Coen *et al.,* 1999; Lenihan *et al.,* 2001; Tolley and Volety, 2005; Tolley *et al.,* 2006). These fishes use the oyster reef as a spawning and feeding habitat and as shelter from predators. Resident oyster reef fishes typically feed on benthic invertebrates such as amphipods, mud crabs, and grass shrimp but can also prey on benthic fishes (Breitburg, 1999; Lenihan *et al.,* 2001). The naked goby, striped blenny, and skilletfish attach their eggs to the insides of recently dead, clean, articulated oyster shells, and the oyster toadfish attaches its eggs to the underside of consolidated oyster shells (Breitburg, 1999; Coen *et al.,* 1999). Resident reef fishes have been observed to swim quickly into the shell matrix of the oyster reef in the presence of a predatory fish or due to the sudden movement of a diver instead of swimming along the substrate surface or up into the water column (Coen *et al.,* 1999).

Many transient fish species have been found on oyster reefs, and several are recreationally or commercially valuable, including Atlantic menhaden (*Brevoortia tyrannus*), tautog (*Tautoga onitis*), striped bass (*Morone saxatilis*), and Spanish mackerel (*Scomberomorus maculatus*) (Breitburg, 1999; Harding and Mann, 2001; Lenihan *et al.,* 2001). Atlantic croaker (*Micropogonias undulatus*), Atlantic menhaden, bluefish (*Pomatomus saltatrix*), and striped bass are all found in greater abundances near oyster reefs compared to habitats such as sand bars (Harding and Mann, 2001). Many transient species, including speckled seatrout (*Cynoscion nebulosus*), weakfish (*Cynoscion regalis*), southern flounder (*Paralichthys lethostigma*), and Spanish mackerel have been found to eat reef resident fish species (Lenihan *et al.,* 2001). Striped bass frequent reefs to feed on the benthic fishes (e.g., naked gobies) and crabs found in and around dead and live oysters (Breitburg, 1999; Harding and Mann, 2001). Juvenile striped bass also feed on naked goby larvae, one of the most abundant fish larvae in Chesapeake Bay tributaries during the summer (Breitburg, 1999). Other species of fish that feed on benthic invertebrates found on oyster reefs include spot (*Leiostomus xanthurus*) and black drum (*Pogonias cromis*) (Breitburg, 1999).

Fish are not the only species that utilize oyster reefs as habitat. Several species of decapod crustaceans are found on oyster reefs: *Petrolisthes armatus*, *Panopeus* spp., *Eurypanopeus depressus*, *Menippe mercenaria*, *Alpheus heterochaelis,* and *Palaemonetes pugio* (Zimmerman *et al.,* 1989; Wenner *et al.,* 1996; Coen *et al.,* 1999; Luckenbach *et al.,* 2005; Tolley and Volety, 2005; Tolley *et al.,* 2005, 2006). The xanthid crab (*Panopeus herbstii*) is a predator of the eastern oyster and is generally found along the boundaries of oyster reefs (McDermott, 1960; McDonald, 1982). In contrast, the flatback mud crab (*E. depressus*) is an omnivore that uses the narrow spaces between dead shells and living oysters as shelter from predation and to avoid dessication (Grant and McDonald, 1979; McDonald, 1982). The porcelain crab (*P. armatus*) is also abundant in oyster clusters and among dead articulated shells, reaching up into the water column perched atop oyster clusters to filter feed (Caine, 1975; Tolley and Volety, 2005). Penaeid and caridean shrimp such as grass shrimp (*Palaemonetes* sp.) are also frequently found on oyster reefs and serve as an important trophic link in both detrital and higher food webs (Coen *et al.,* 1999). Grass shrimp also probably use the reef to avoid predators (Posey *et al.,* 1999). In addition, many organisms use the oyster reef in varying ways. Benthic reef invertebrates, such as amphipods, are food for crabs and shrimp that then are eaten by resident and transient fish species. The oyster reef is also used as shelter by species such as resident mud crabs and grass shrimp that use the spaces in and around oysters to avoid predation.

In a comprehensive study, using carbon and nitrogen isotopes, Abeels (2010) examined the trophic transfer from the water column to various organisms in an oyster reef ecosystem. The organic matter sources, amphipods, and worms are at the lowest level and are consumed by oysters, resident crabs, shrimp, and fishes. The oysters, crabs, and shrimp are then consumed by other resident crabs and fish species. Transient fish species such as *Lutjanus* spp. come to the reef to feed on the resident crab, shrimp, and fish species. In a separate study, Wasno *et al.* (2009) investigated the trophic transfer from within the oyster reef community to 12 species of predatory fish. While the species of fish varied with season, the diet of fish caught during the wet and dry seasons did not differ significantly. Prey species belonging to the decapod crustaceans (*Eurypanopeus depressus*, *Panopeus* spp., and *Xanthidae* spp.) that are almost exclusive to oyster reefs occurred in the majority of stomachs and contributed to >43 percent of the relative importance index. Combined, results from both of these studies illustrate the importance of oyster reefs not only in oyster reefs serving as a habitat, but also in trophic transfer and secondary production.

Filtration

Oysters filter tremendous amounts of water while feeding (Newell, 1988). By filtering water column particulates, nutrients, sediment, and phytoplankton, oyster reefs increase light penetration to deeper layers, thus promoting the growth of SAV and, via denitrification, reduce anthropogenic nitrogen and minimize impacts of eutrophication (Grabowski and Peterson, 2007; Newell, 2004; Newell *et al.,* 2002). For example, the decline in oyster populations in the estuaries along the eastern seaboard has coincided with increases in nutrient loading and a decrease in water quality (Paerl *et al.,* 1998). This has resulted in ecosystem perturbations such as hypoxia and food webs dominated by microbes, phytoplankton, and nuisance pelagic species such as jellyfish (Breitberg, 1992; Jackson *et al.,* 2001; Lenihan and Peterson, 1998; Paerl *et al.,* 1998; Ulanowicz and Tuttle, 1992). Experiments have also indicated that oysters, through their filtration, increased light penetration by consuming algal production and increasing microphytobenthos (Dame *et al.,* 1989; Porter *et al.,* 2004). Field studies have demonstrated that oysters in North Carolina decreased chlorphyll-a levels in the water column by 10-25 percent and fecal coliform bacteria by 45 percent (Cressman *et al.,* 2003). Increased nutrient loading and/or turbidity is extremely detrimental to SAV habitats. For example, nitrogen loading of 30 Kg N ha^{-1} yr^{-1} resulted in a decrease of 80-96 percent loss in SAV coverage in Waquoit Bay, Massachusetts. A 20 percent reduction in seagrass coverage in Chesapeake Bay resulted in an annual loss of $1-4 million of fishery value annually (Kahn and Kemp, 1985). In addition, a study by National Research Council (2004) estimated that a 20 percent improvement in water quality along the western shore of Maryland was worth $188 million for shore beach users, $26 million for recreational boaters, and $8 million for striped bass fishermen.

Mitigation of Wave Activity and Carbon Sequestration

In addition to providing habitat and secondary production, oyster reefs, with their calcareous shells and three-dimensional structure, also attenuate wave action and reduce erosion, thereby protecting other valuable habitats such as mangroves, sea grasses, and marshes in the estuarine environment (Henderson and O'Neil, 2003; Meyer *et al.,* 1997). Oyster reefs also promote sedimentation and, therefore, benefits the growth of SAVs. Additionally, oysters also sequester CO_2 from the water column via formation of calcium carbonate shells and, thus, potentially reduce the concentration of greenhouse gases (Peterson and Lipcius, 2003).

Environmental Sentinels

Sedentary, benthic filter-feeding organisms, such as oysters, clams, and mussels, given their enormous filtration capacity, are particularly effective in taking up hydrocarbons via filtration and ingestion and are, therefore, susceptible to the negative effects of these contaminants. For this reason, bivalve mollusks, such as oysters and mussels, are used worldwide as sentinel organisms in coastal environments to examine trends of contaminant levels, as well as ecological impairment (NOAA Status and Trends Program; O'Connor and Laurenstein, 2006).

Attributes People Care About

Oyster reefs in the SWFS support attributes of the marine environment that people care about. These attributes are directly related to ecosystem services provided by the southwest Florida coastal and marine ecosystem:

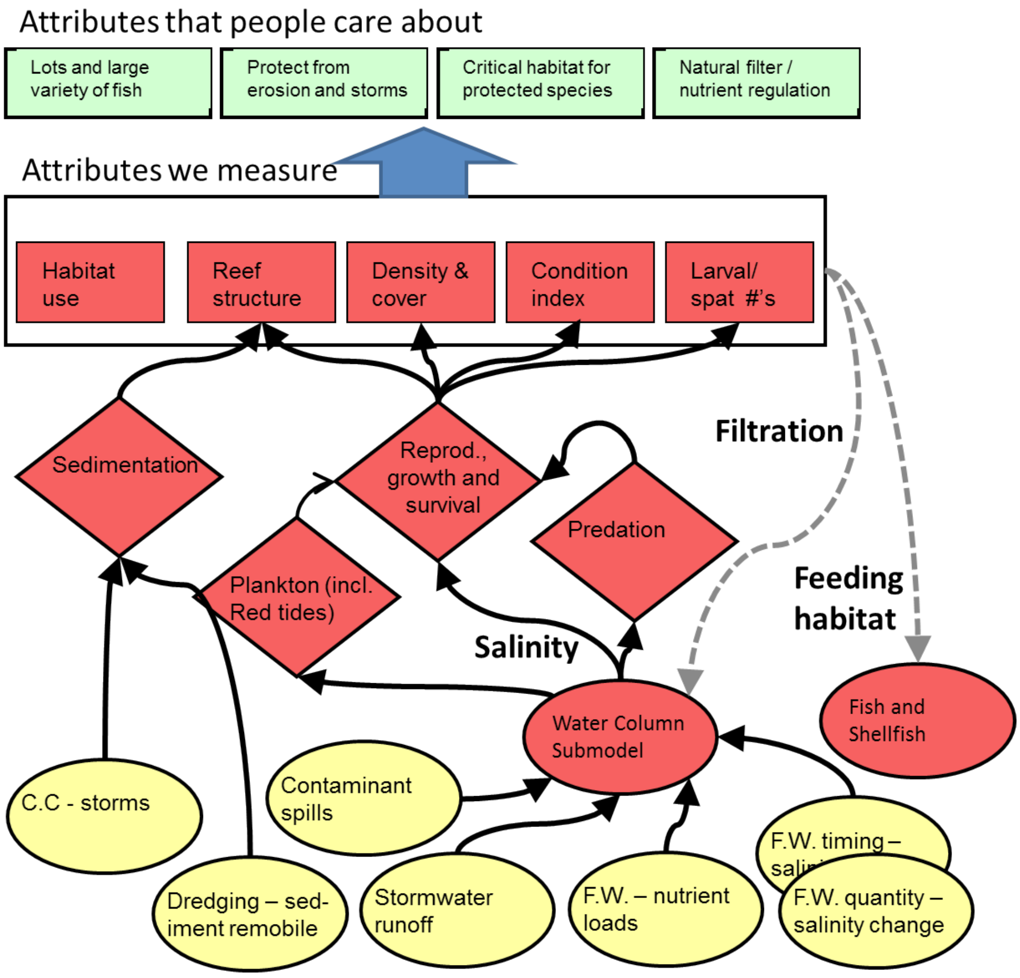
- Diverse fish, crustaceans, and other invertebrate populations
- Coastal erosion and boat wake mitigation
- Critical nursery and food habitat for recreationally- and commercially-important species
- Natural filter for phytoplankton, detritus, bacteria, and contaminants, resulting in enhanced water clarity and increased water quality
- Carbon sequestration

Diverse Fish, Crustaceans, and Other Invertebrate Populations

Oyster reefs are important locations for recreational fisherman in southwest Florida. For example, a recent study by Wasno *et al*. (2009) showed that fish such as sheepshead, snook, redfish, catfish, snapper, etc., obtain 43 percent of their diet (relative importance index) from four crustacean species that only live within an oyster reef. Live oyster reefs have higher diversity and species richness compared to reefs with dead oysters or no oysters (Tolley and Volety, 2005) and harbor a tremendous diversity of organisms (Grabowski and Peterson, 2007; Wells, 1961). Oyster reefs and adjoining seagrass beds and/or mangrove areas are commonly targeted by recreational fishermen and fishing guides in southwest Florida.

Coastal Erosion and Protection Against Boat Wakes

By reducing wave height, current velocities, and sediment resuspension, oyster reefs protect sea grasses and mangroves from erosion, saving these valued ecosystem communities.



Oyster reef submodel diagram for the Southwest Florida Shelf.

The reduction in turbidity, sedimentation, and erosion not only aids the ecology, but also has economic benefit derived from these habitats. Similar to sea grasses, oyster reefs are self perpetuating and require little or no time or expense in maintaining them.

Natural Filtration

The biggest and most important benefit of oyster reefs to an ecosystem is their tremendous filtration capacity. According to Newell (1988), individual oysters filter 4-40 L/h. This filtration removes detritus, phytoplankton, contaminants, and bacteria, resulting in greater light penetration, thus promoting the growth of seagrasses and benthic microalgae. Sequestration of nitrogen via removal of organic matter from the water column also decreases impacts of eutrophication and promotes denitrification.

Carbon Sequestration

Oysters secrete calcium carbonate shells from seawater, thereby removing CO_2 from the water column (and thus atmosphere) and contributing to a reduction in greenhouse gases. The shells are insoluble and, thus, form a carbon sink in the coastal and estuarine realms.

Attributes We Can Measure

Given the ecological and economic benefits of oyster reefs, monitoring of oyster reefs by various local, state, and federal agencies has been in place for many years. In southwest Florida, a monitoring program to support the Comprehensive Everglades Restoration Plan (CERP) includes monitoring of oyster responses (RECOVER, 2007). Typical oyster responses that are measured include:

- Spatial extent
- Living density
- Larval recruitment
- Growth and survival of juvenile oysters
- Intensity and prevalence of diseases
- Reproductive condition

Spatial Extent

Along the southwest Florida estuaries and coast, the distribution and coverage of oyster reefs is influenced by salinity, substrate and food availability, larval recruitment, as well as the timing and duration of freshwater inflows into the estuaries (Volety, 2008; Volety *et al.,* 2009). Recent decades have witnessed declining oyster populations throughout the world. For example, Beck *et al.* (2011) estimated that oyster reefs are at less than 10 percent of their prior abundance and that ~85 percent of oyster reefs have been lost globally. Such decreases have coincided with decreases in water quality and clarity (Newell *et al.,* 1988). Some of the main reasons for declines in oyster reef abundance and distribution include diseases (Burreson and Ragone-Calvo, 1996; Soniat, 1996; Volety *et al.,* 2000), overharvesting, dredging, altered watershed, and salinity (Volety *et al.,* 2009).

Living Density

The density of living oysters varies between estuaries (100-4000+ oysters/square meter). Live oyster density, an indirect measure of reef productivity, also varies considerably along an estuarine salinity gradient and in response to various stressors that affect oyster growth and survival. Patterns attributable to human alterations in freshwater flow were detected previously in the Blackwater and Faka Union estuaries in the Ten Thousand Islands (Volety and Savarese, 2001; Volety, 2007). Similarly, oyster-living density varies with yearly freshwater inflows in the Caloosahatchee Estuary (Volety *et al.,* 2010). Since salinity has profound influence on spat recruitment, predation, survival, and fecundity (Volety *et al.,* 2009, 2010), differences in the living density of oysters between estuaries is not surprising. In addition to salinity, depending on the amount of freshwater that flows into the estuaries due to regulatory freshwater releases and/or watershed runoff, this may result in physical flushing of larvae to downstream locations, where substrate may be limited. For this reason, for relatively unaltered estuaries, the focus of oyster reef development occurs at mid-estuary, where salinity and food conditions tend to be favorable for oysters (Volety and Savarese, 2001; Savarese and Volety, 2008; Volety *et al.,* 2010).

Larval Recruitment

Oyster spat recruitment is typically monitored using old adult oyster shells strung together by a weighted galvanized wire or settling plates made of calcium carbonate cement and deployed at a sampling location. Oyster spat settlement is monitored monthly by counting the number of spat settled on the underside of strung shells (or plate), and spat settlement is expressed as the number of spat settled per oyster shell per month. Oysters reproduce during late spring-early fall in southwest Florida, and monitoring of spat recruitment is typically conducted between the months of May and October in southwest Florida estuaries (Volety, 2008; Volety *et al.,* 2009; Volety *et al.,* 2010). Since oyster reproduction and spat recruitment are influenced by salinity, temperature, food availability, and substrate quality, any environmental perturbations will negatively impact spat recruitment and survival and, hence, next year's class of oysters, resulting in poor living density of oyster during subsequent years.

Growth and Survival of Juvenile Oysters

Juvenile oysters grow at a faster rate than adult oysters and, thus, make excellent indicators to measure the role of water quality on the survival and growth of oysters (Volety *et al.,* 2010). Juvenile survival and growth is influenced by salinity, temperature, food quality and quantity, predators, and dissolved oxygen (Shumway, 1996). Higher salinities typically attract more predators and disease and, thus, oysters are more susceptible to predation and mortality (White and Wilson, 1996). To discriminate between growth and survival of juvenile oysters due to water quality and/or predation, juvenile oysters are deployed in open and closed bags and their survival and growth monitored (Volety *et al.,* 2010). The responses of juvenile oysters placed in closed wire-mesh bags indicate growth and/or mortality due to water quality; responses of oysters in open cages denote growth and/or mortality due to predation and water quality, thus giving us an estimation of the role of predation in these estuaries. These results are extremely useful in modeling or estimating oyster populations at various salinity and inflow regimes. This method was successfully employed by Volety *et al.* (2003) in the Caloosahatchee River and estuary and by Volety and Savarese (2001) in the Ten Thousand Islands. Adult oysters normally occur at salinities between 10 and 30‰, but they tolerate salinities of ~2 to 40‰ (Gunter and Geyer, 1955). Occasional, short pulses of freshwater inflow can greatly benefit oyster populations by reducing predator (e.g., oyster drill, whelk) and parasite (e.g., *Perkinsus marinus*) impacts (Owen, 1953), but excessive freshwater inflow may kill entire populations of oysters (Gunter, 1953; Schlesselman, 1955; MacKenzie, 1977; Volety *et al.,* 2003; Volety *et al.,* 2010; Bergquist *et al.,* 2006). Therefore, controlled freshwater releases could be used in adaptive management to mitigate disease and predation pressure on oysters.

Intensity and Prevalence of Disease

For nearly 50 years, eastern oyster populations along the east and Gulf coasts of the United States have been ravaged by the highly pathogenic protozoan parasite, *Perkinsus marinus* (aka Dermo; Mackin, 1962; Andrews and Hewatt, 1957; Andrews, 1988; Burreson and Ragone-Calvo, 1996; Soniat, 1996). Higher salinities and temperatures significantly enhance *P. marinus* infections in oysters (Andrews, 1988; Burreson and Ragone-Calvo, 1996; Chu and Volety, 1997; Soniat, 1996; Volety *et al.,* 2003, 2009). The presence and intensity of the disease organism is typically assayed using Ray's fluid thioglycollate medium technique (Ray, 1954; Volety *et al.,* 2000; Volety *et al.,* 2003, 2009). Samples of gill and digestive diverticulum are incubated in the medium for four to five days. *P. marinus* meronts enlarge in the medium and stain blue-black with Lugol's iodine, allowing for visual identification under a microscope. Prevalence of infection is calculated as the percentage of infected oysters (Mackin, 1962). The intensity of infection is recorded using a modified Mackin scale (Mackin, 1962) in which 0 = no infection, 1 = light, 2 = light-moderate, 3 = moderate, 4 = moderate-heavy, and 5 = heavy.

Temperature and salinity profoundly influence the disease susceptibility of oysters, with higher temperatures and salinities resulting in a higher prevalence and intensity of *P. marinus* infections (Chu and Volety, 1997; Soniat, 1996; La Peyre *et al.,* 2003; Volety, 2008; Volety *et al.,* 2009). This trend has been confirmed in other southwest Florida estuaries, including those in the Ten Thousand Islands (Volety and Savarese, 2001; Savarese and Volety, 2008).

Oysters with infections above moderate levels quickly die out if temperatures and salinities remain high. Given that >80 percent of infected oysters can encounter mortality (Andrews, 1988), the impact of salinity on the survival of adult oysters cannot be underestimated. During warmer months (summer-fall), southwest Florida estuaries experience heavy rainfall and watershed runoff, as well as regulatory freshwater releases that depress salinities. During winter, when temperatures are cooler, there is little or no rainfall or watershed runoff, resulting in high salinities and, at times, hypersaline conditions within the estuary. The antagonistic effects of high temperature/low salinity (summer), and low temperature/high salinity (winter) keeps disease in check at low to moderate levels; however, in the absence of freshwater releases during winter, salinities become high and oysters are prone to disease, as well as predation. Similarly, if high volumes of freshwater are released, especially for extended periods (>1-2 weeks), salinities tend to be depressed, resulting not only in mitigation of the parasite and predators, but also in increased mortality of larval, juvenile, and adult oysters.

Reproductive Condition

The reproductive condition is used to estimate fecundity or the potential of oysters to engage in normal reproductive activity (or lack thereof). Histological analysis is typically used to examine gonadal state and reproductive potential of oysters and gametogenic stage identified under a microscope according to Fisher *et al.* (1996) and the International Mussel Watch Program (1980). Gonadal portions of the sections were examined by light microscopy to determine gender and gonadal condition. This method has been previously used successfully to identify reproductive patterns of oysters in southwest Florida estuaries (Volety and Savarese, 2001; Volety *et al.,* 2003) and to recommend alteration of inflow patterns to ensure survival of oyster spat during the reproductive season.

It appears that oysters in the Caloosahatchee Estuary continuously spawn from April to October, a result corroborated by changes in the condition index and spat recruitment at various sampling locations (Volety *et al.,* 2010). This trend contrasts with that of oysters from the northeastern United States (Shumway, 1996) and Chesapeake Bay (Southworth *et al.,* 2005), where reproduction of oysters is limited to a few months in the summer (August-September). This reproductive trend of oysters in southwest Florida estuaries has significant management implications. For example, minimizing large freshwater releases during summer-fall, when oysters are spawning in the estuary, would result in favorable salinity conditions and larval retention within the estuary, resulting in higher recruitment and possibly higher adult densities in subsequent months. Due to high freshwater flows during summer months, larvae are flushed to downstream locations where substrate may not be available. High spat recruitment at downstream locations due to flushing activity may not be beneficial to the system as a whole, as higher salinity conditions at these locations attract predators and diseases (Shumway, 1996; White and Wilson, 1996; Volety, 2007; Volety *et al.,* 2009), resulting in mortality. Decreasing the duration and magnitude of high flows during summer (wet) and releasing base flows during winter (dry) will minimize extreme salinity fluctuations that are detrimental to oysters.

Drivers of Change in Oyster Reefs

Pressures are the direct cause of change in the ecosystem. The source of pressures affecting oyster reefs beds in the SWFS area, on a local scale, include coastal development and freshwater inflows into the estuaries due to regulatory releases and/or watershed runoff, increased sedimentation, input of excessive nutrients, and contaminants. On a more regional or global scale, pressures result from regional inputs of nutrients, which contribute to a general increase in nutrient concentrations in the coastal ocean, climate change, and the effects of rising carbon dioxide concentrations on ocean water chemistry. These pressures have a tremendous impact on the development of oyster larvae and the formation/dissolution of calcium carbonate shell under low acidic conditions.

Coastal Development

Local-scale alterations in the watershed from coastal/watershed development results in run-off of nutrient- and contaminant-laden sediment into rivers and estuaries. This contributes to the development of macroalgae and harmful algal blooms. Blooms smother the oyster beds and deplete oxygen when they decompose and negatively impact oysters and their early life stages with biotoxin production (Leverone *et al.,* 2006, 2007). Contaminants also negatively impact oysters by increasing disease susceptibility and survival (Chu and Hale, 1994). Dredging and filling of coastal areas for navigation and utilization of shell in construction also depletes suitable substrate and negatively affects oyster reef development.

Climate Change and Sea-Level Rise

Carbon dioxide levels in the atmosphere have been rising since the beginning of the Industrial Revolution. Present day atmospheric CO_2 concentrations of 385 ppm represent a nearly 30 percent increase over pre-industrial values, with concentrations forecast to surpass 700 ppm by the end of the century (IPCC, 2007). These increases in CO_2 concentrations are believed to cause increases in atmospheric and oceanic temperatures, changes in the carbonate chemistry of seawater and widespread melting of snow and ice, and rising sea levels (IPCC, 2007). Recent studies have shown that the CO_2 trends anticipated by the IPCC (2007) study can have significant impacts on the calcification rates and physiology of planktonic and benthic organisms, including shellfish (Fabry *et al.,* 2008). In fact, the impact of acidic waters on bivalves has been investigated since the 1940s (Loosanoff and Tommers, 1947). More recently, reduced CO_2 levels have been shown to decrease calcification (Gazeau *et al.,* 2007; Kurihara *et al.,* 2009; Miller *et al.,* 2009), reduce shell growth (Berge *et al.,* 2006; Michaelidis *et al.,* 2005), and increase mortality (Talmage and Gobler, 2009) in different species and life stages of marine bivalves.

Mechanisms of Change in Oyster Reefs

The principal threats to oyster reefs in the SWFS mostly occur through four pathways: watershed development and input of nutrients and contaminants; freshwater runoff from the watershed and regulatory freshwater releases; increased sedimentation; and dredging and removal of substrate required for larval settlement and reef growth.

Oyster Reef Status and Trends

Anecdotal evidence, as well as archived photographic evidence, suggests that the coverage of oyster reefs in southwest Florida has drastically decreased. Current coverage of oyster reefs in the Caloosahatchee Estuary-Ten Thousand Islands is about 0.1-1 percent of the accommodation space (as defined by the area where salinity is favorable for oyster growth). Healthy estuaries along the Gulf of Mexico have oyster reef coverage of about 1-5 percent accommodation space (RECOVER, 2009; Volety *et al.,* unpublished results). The situation along the southwest Florida coast follows a general decline in oysters worldwide. Oyster reefs are at less than 10 percent of their prior abundance in most bays and ecoregions. It has been estimated that there is an 85 percent loss of oyster reef ecosystems globally (Beck *et al.,* 2011). Most of the loss is due to timing, duration, and quantity of freshwater inflows into the estuaries, as well as increased sedimentation and contaminants resulting from watershed runoff. With a reduction and redirection of freshwater Everglades discharge (along with many other changes to the coastal wetlands), many of these historical oyster bars and banks have been lost.

Topics of Scientific Debate and Uncertainty

While the relationship between salinity and *P. marinus* prevalence and intensity has been well established through laboratory (Chu and Volety, 1997; La Peyre *et al.,* 2003) and field studies (Burreson and Ragone-Calvo, 1996; Soniat, 1996), the importance of duration, frequency, and magnitude of freshwater inflows into estuaries and how they influence *P. marinus* infections is not clear. In addition, the role of freshwater inflows on the early life stages of oysters is unclear and is necessary for managing freshwater inflows into southwest Florida estuaries. While it has been shown that contaminants affect immune responses (Anderson, 1993; Pipe and Coles, 1995), energy reserves (Capuzzo, 1996), and exacerbates *P. marinus* infections in oysters (Chu and Hale, 1994; Anderson *et al.,* 1996), their effects on the early life stages and, especially, on the F-2 generation is unclear. Similarly, the effects of harmful algal blooms on the survival and metamorphosis of early life stages of oysters and long-term reproductive impacts on oysters are unclear. Recent studies investigating the effect of elevated CO_2 levels under scenarios of predicted global climate change have yielded contrasting results depending on the species examined. Little or no information exists on the effects of elevated CO_2 levels in seawater, and how it may impact growth and survival of larval oysters is unclear.

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Habitat: Benthic Offshore

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In a nutshell:

- Benthic offshore habitats are used by valued fish and invertebrate species, such as red drum, pink shrimp, and stone crab.
- The live bottom fauna of the benthic offshore habitat is the source for the large variety of shells that comprise the beaches along the southwest Florida coast and are a distinctive feature of the region.
- Sand mining, for beach renourishment and fishing, affects benthic offshore habitats both directly and indirectly.
- Climate change and coastal eutrophication are major drivers of change in benthic offshore habitats.

Benthic offshore habitats in southwest Florida include hardbottom communities with a diverse epibiota of hard and soft corals and macroalgae that are used by abundant populations of fish species. The hardbottom areas are typically at intermediate depths where limestone outcroppings occur. A thin veneer of overlying sand, when combined with storms and waves, can cause scouring and dislodging of epibiota and transport to barrier island beaches. The shallow depths are colonized by pen shells and quartz sands with shells and other mollusks, such as fighting conchs (*Butrycon* spp.) and calico scallops (*Argopectin* spp.). Deeper depths contain low-relief limestone with barrel sponges interspersed with areas of crushed shell and carbonate sediments and occasional beds of paddle grass (*Halophila decipiens*), especially in the Cape Sable Province and northwestern Florida Bay.

The Hourglass expeditionary cruises, initiated by the Florida Board of Conservation Marine Research Lab, occurred from 1965-1967 (Joyce and Williams, 1969). The Hourglass program provided the first characterization of offshore benthic habitats. Researchers sampled only a small area of the total shelf on two transects offshore of Egmont Key and Sanibel Island. At shallow stations (6 m), they found quartz and crushed shell with living and dead mollusks (*Pinnidae, Butrycon* spp.). Mid-depth stations (18 m) contained abundant limestone outcroppings with up to 1 m of relief, colonized by sponges, alcyonarians, and stony corals (*Solenastrea hyades* and *Cladocora arbuscula*). The smooth areas in between were typically quartz sand colonized by *Halophila decipiens* and *Caulerpa* spp. Deep stations had low relief limestone and large barrel sponges. Smooth areas contained crushed shell and white calcareous silt. Calcareous algae (*Lithothamnion* spp.) and brown alga *Sporochnus* sp. were also observed at this depth. At 55 m, a generally smooth bottom with sponges and the bryozoans *Steganoporella magnilabris* and *Hippopetraliella marginata* was observed.

The live bottom was characterized by epifaunal assemblages associated with limestone outcroppings. Rarely, however, were these areas devoid of surficial sediments. Typically, the live bottom is covered by a layer of sand, shell, and carbonaceous silt from 1 to 10 cm in thickness. A substantial macroinfaunal community existed that far outnumbered the larger epifaunal components in taxa and individuals. This community differed markedly from the soft bottom infaunal community immediately adjacent, which did not exhibit the associated live bottom epifaunal components. There exists a rich flora on the shelf with seaweeds of tropical and subtropical genera (Dawes, 2004). A large number of perennial tropical species were collected in the 20-80 foot range. Seasonal patterns indicate a late spring to summer growth period, maturing in late summer and disappearing in the early winter.

Culter (1988) sampled macrofauna from the seafloor for both live bottom and soft bottom areas on the continental shelf. The live bottom infaunal habitat consisted of a thin veneer of sediments overlying a limestone bottom, marked by conspicuous epifauna such as sponges, gorgonians, and corals. The soft bottom was adjacent to the live bottom habitat and characterized by a lack of conspicuous epifauna and a thicker layer of sediments, although similar in sediment. Underwater video was used to target areas with the potential of becoming sand mining sites with the adjacent live bottom. For the live bottom stations, polychaetes accounted for an overall average of 38.6 percent (Sd., 10.7 percent); molluscs, 21.5 percent (Sd., 1.5 percent); crustaceans, 36.8 percent (Sd., 10.7 percent); with other minor groups accounting for an additional 3.5 percent of the fauna. For soft bottom stations, polychaetes averaged 50.6 percent (Sd., 9.1 percent) of the fauna; molluscs, 9.9 percent (Sd., 4.4 percent); crustaceans, 22.7 percent (Sd., 9.7 percent); and miscellaneous groups an additional 17 percent of the total fauna. A list of taxa indicative of live bottom and soft bottom were provided.

The Minerals Management Service funded a biological inventory and sediment grain size analysis of an area offshore of Tampa Bay, and an extensive benthic offshore inventory containing species lists and descriptions was subsequently published (Brooks *et al.,* 2004; Brooks *et al.,* 2006). The continental shelf contained many shoal and ridge features and supported a diversity of polychaetes, bivalves, and amphipods (Posey *et al.,* 1998).

Role of the Ecosystem

Coastal waters are the spawning grounds, nurseries, shelter, and food source for numerous finfish, shellfish, birds, and other species. These areas also provide nesting, resting, feeding, and breeding sites for over 75 percent of Florida's waterfowl and other migratory bird species. Superimposed on these important coastal areas is the fact that they are the most densely populated areas in the U.S., accounting for only 17 percent by area, but more than 53 percent of our nation's population (Crossett *et al.,* 2004; EPA, 2008). All of the nation's coasts are popular vacation destinations, with about 180 million people visiting U.S. beaches each year. Beach monitoring and reporting data for 2008 indicated that more than 32 percent of the nation's beaches had at least one advisory or closure in effect during swimming season (EPA, 2008). These advisories or closings are typically issued as a result of monitoring by state agencies when elevated bacterial levels are detected in the water, often the result of rainfall runoff or sewage spills.

Fish use of benthic offshore habitats has been demonstrated for commercially valuable species. The low relief hardbottom habitats have been used by red snapper to feed on infaunal invertebrates (Szedlmayer and Lee, 2004; Wells *et al.,* 2008). Biogenic structures (e.g., tubes, mounds, pen shells, and burrows) constructed by invertebrates provide distinct habitat with which many juvenile fish have been found to use as a refuge from predation (Kaiser *et al.,* 1999).

Stone crabs (*Menippe* spp.) support a valuable commercial fishery in the Gulf of Mexico, with most of the catch occurring on the continental shelf. Florida landings increased from 172,000 kg per fishing season (15 October-15 May) in the early 1960s to over 1 million kg since 1988. The 1990 landings were valued at over $15 million (Restrepo, 1992). Given the value of this fishery, there is surprisingly little known about this essential habitat or prey items. There are reports on the life history and population information (Ehrhardt *et al.,* 1990; Gerhart and Bert, 2008); however, landings data are the principal monitoring tool used by fisheries management. No research has documented the effects of "ghost crabs" on other epibenthic organisms or fishes. Observations of ghost traps on the continental shelf suggest that gear impacts from the stone crab fishery needs further study (Milbrandt *et al.,* 2010; Grizzle *et al.,* 2010).

Attributes People Care About

There are many attributes of benthic offshore habitats that people care about. In the Barrier Islands Province, beaches are popular shelling destinations. The benthic offshore habitats are the source of the shells, which are transported to the barrier islands during tropical storms and cold fronts. Changes affecting the productive offshore habitats or delivery could threaten the tourism economy. In Lee County, tourism employs one out of every five people, with over five million visitors per year generating more than $3 billion in economic revenues (http://www.leevcb.com/statistics/index.php). Commercially valuable fish and invertebrate species (e.g., red drum, pink shrimp, stone crab) use the shelf and estuaries for part of their life cycle and depend on the offshore benthic habitats.

There are diverse molluscan communities that exist on the continental shelf and have made Sanibel Island a popular tourist destination for shelling. Among these are pen shells (*Pinnadae*), which were described on Sanibel beaches as abundant and potentially important attachment substrates for seaweeds and other invertebrates (Perry, 1936). In the northern Gulf, the suitability of pen shells as a habitat for marine invertebrates and algae was demonstrated for both sessile and mobile animals (Munguia, 2004). Experimental destruction of pen shell habitat resulted in loss of habitat for other animals or led to significant spatial rearrangement of the community that has effects on animal migration and location extinction rates (Munguia and Miller, 2008).

Attributes We Can Measure

Recently, a special issue on mesophotic coral reefs discussed the biology, ecology, and global distribution of deep coral reef habitats (Hinderstein *et al.,* 2010). Many of these habitats are difficult to sample because of the need for submersibles and technical diving. At the shelf break, 200 km from the southwest Florida coast, a mesophotic reef was discovered and named Pulley Ridge after Dr. T.E. Pulley, malacologist, founder and long-time director of the Houston Museum of Natural Science. Pulley Ridge is a 100 plus km long series of north to south drowned barrier islands on the SWFS (Jarrett *et al.,* 2005; Hine *et al.,* 2008). The ridge has been mapped using multibeam bathymetry, submarines, and remotely-operated vehicles, as well as a variety of geophysical tools. The ridge is a subtle feature about 5 km across with less than 10 m of relief. The shallowest parts of the ridge are about 60 m deep. At this depth, the southern portion of the ridge hosts an unusual variety of zooxanthellate scleractinian corals, green, red, and brown macroalgae and, typically, shallow water tropical fish. A more detailed description and imagery from the site were produced in an expeditionary cruise with submersibles and technical divers (Culter *et al.,* 2006).

A multi-institution effort was conducted from 2008-2010 to characterize the benthic communities off Sanibel Island and to understand the distribution and abundance of macroalgae (Loh *et al.,* 2010). Large areas of the shelf near Sanibel were mapped with hydroacoustic and underwater video. Prior to this, maps and characterization of the benthic habitats did not exist. Along with extensive mapping and characterization of the macroalgal communities, there were efforts to identify sources of nutrients, including a submarine groundwater analysis. Together with a hydrodynamic model and experiments to evaluate the effects of grazers on macroalgae, this was the first systematic research effort on the inner continental shelf since the Hourglass cruises in the 1960s. Extensive descriptions of the macroalgal community and periods of peak biomass are described at several stations on the continental shelf.

Drivers of Change

Benthic offshore habitats are usually considered to be geographically isolated from drivers such as landscape alterations and water management practices caused by development. However, eutrophication can cause pressures, such as algal overgrowth and an intensification of red tide or other phytoplankton blooms that may lead to pockets of hypoxia or loss of available light for corals and benthic macroalgae (Figure 1). Climate change is a farfield driver thought to bring increased frequency and intensity of storms which are thought to play a critical role in the creation and maintenance of hardbottom habitats. Development in southwest Florida, especially the development of beaches in the Barrier Islands Province, is also a principal driver. The need for beach renourishment projects emerged as a result of a combination of development plus storm waves and erosion. Sand mining is a pressure that can have direct and indirect effects on the live bottom patch reefs, pen shell

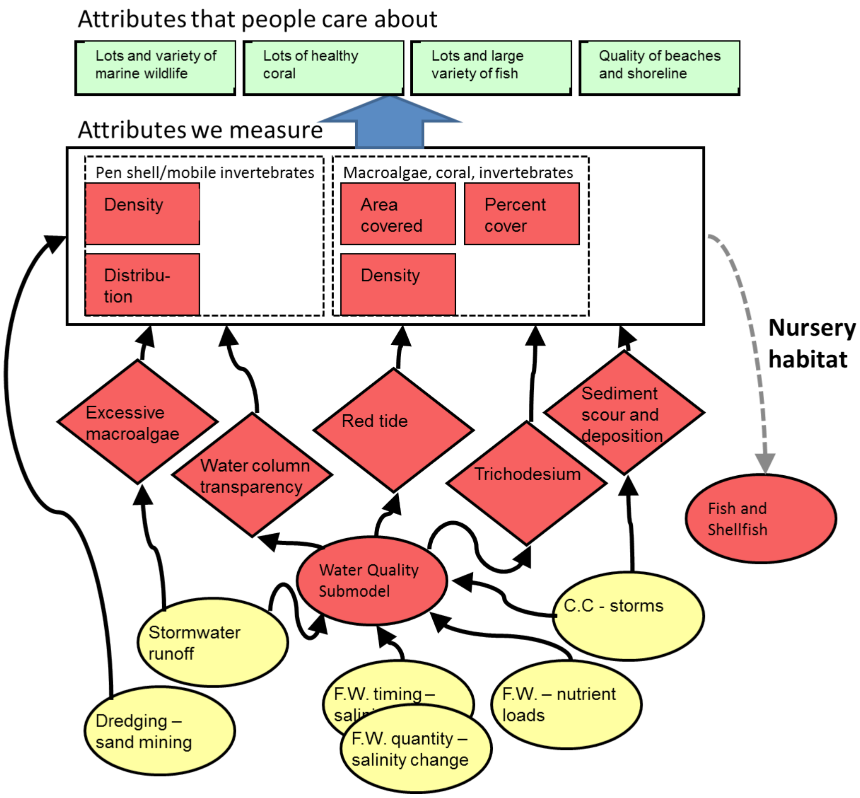

Figure 1. Benthic offshore submodel diagram for Southwest Florida Shelf.

habitats, and shell hash habitats typical of the continental shelf. Increased fishing pressure can change the trophic structure and affect benthic offshore habitats.

In a recent assessment of climate change impacts on U.S. coastal areas, several key climate change drivers were evaluated (Scavia *et al.,* 2002). Sea level change, alterations in precipitation patterns, changes in the frequency and intensity of coastal storms, and increased levels of CO_2 were all viewed as threats to benthic offshore habitats.

With an increase in storm frequency and intensity, the principal pressures are scouring and sediment transport. The natural history and geology of the continental shelf was elaborated in a recent review by Hine and Locker (2011). The SWFS is described as a very wide, low energy, sediment-starved shelf seaward of the west-central Florida barrier islands system. This inner shelf presents a wide variety of sand ridges up to 4 m thick and separated by extensive areas of exposed limestone. This geomorphology of the barrier islands subregion suggests that circulation is an important driver of the location and complexity of epibiotic communities. A thin veneer of sediments overlays the productive live bottom habitats and suggests that scouring is an important physical disturbance mechanism. Frequent strandings of large numbers of invertebrates and large amounts of macroalgae on barrier island beaches supports this hypothesis (Perry, 1936; Dawes, 2004).

Development of landscapes adjacent to beaches is an important driver. As development has increased on the barrier islands along the southwest coast, the need for beach renourishment projects has emerged as a result of a combination of storm waves and erosion (Stapor *et al.,* 1991). Sand mining is a pressure that can have direct and indirect effects on the live bottom patch reefs, pen shell habitats, and shell hash habitats typical of the continental shelf.

Overfishing is a driver that has changed the trophic structure of many marine ecosystems (Jackson *et al.,* 2001), resulting in changes to benthic habitats. This results in a pressure such as algal overgrowth of coral reefs (Hughes, 1994). Potential gear impacts as pressures include hook and line litter and damage, vessel groundings, and ghost traps.

Mechanisms of Change

Nutrient-laden freshwater discharges from Lake Okeechobee and loading from the heavily laden agricultural watershed are cited as the principal drivers for water quality degradation (SFWMD, 2009), seagrass losses, and harmful algal blooms (Brand and Compton, 2007) in the Caloosahatchee Estuary. The loss of the continental shelf habitats due to stormwater runoff is largely unknown. The hardbottom and pen shell habitats occupy much of the continental shelf which may not be affected directly by sudden decreases in salinity, but the effects of stormwater runoff may be the result of an indirect effect, such as sedimentation, decrease in light penetration to benthic habitats, or eutrophication. These documented losses and environmental problems have negative effects on the public's perception and aesthetic value of shelf and barrier island habitats. It is expected that southwest Florida will continue to provide opportunities for fishing and diving, with an abundance of large fish, wading birds and shorebirds, and marine mammals.

Benthic offshore habitats are usually considered to be geographically isolated from drivers such as landscape alterations and water management practices. However, eutrophication can cause pressures, such as algal overgrowth and an intensification of red tide or other phytoplankton blooms (Brand and Compton, 2007), which may lead to pockets of hypoxia or loss of available light for corals and benthic macroalgae. The timing and delivery of freshwater and stormwater runoff are important drivers in the bays and estuaries and in the nearshore environment. Given the broad and far-reaching geomorphology of the SWFS, much of the benthic offshore habitats are not affected by local runoff or nutrient loading. However, regional patterns in climate and runoff caused by discharges of nutrient-rich water to the Gulf of Mexico can occur from large systems (e.g., Mississippi River, Peace River, Lake Okeechobee via the Caloosahatchee River).

The Caloosahatchee River/Estuary is a conveyance for excess water in Lake Okeechobee, and large releases have been associated with large-scale increases in benthic macroalgae. Given that the coastal waters are nitrogen limited (Brand and Loh, 2011), it is logical to conclude that large NOx and NH_3 loading from stormwater runoff would result in excessive algal biomass. There is a decreasing gradient of nitrogen and phosphorus from Lake Okeechobee to the Gulf of Mexico, suggesting that Lake Okeechobee is a major source of nutrients to the coastal waters through a combination of conservative (dilution with Gulf waters) and non-conservative (algal/plant uptake) processes. Algal tissues near the mouth of the Caloosahatchee Estuary demonstrated elevated δN15 ratios, suggesting that nutrients in stormwater runoff are being assimilated into macroalgal biomass (Lapointe and Bedford, 2007; Milbrandt *et al.,* 2010).

Status and Trends

Changes affecting the productive offshore habitats could threaten an area well known for shelling and healthy beaches and could have tremendous economic consequences. In Lee County, tourism employs one out of every five people, with over five million visitors per year generating over $3 billion in economic revenues (http://www.leevcb.com/statistics/index.php). Diminished coastal resources and habitats adversely affect the regional economy. Degraded water quality from heavy rains in 2004-2005 resulted in an estimated $40 million loss to the Lee County economy. The Caloosahatchee Estuary shows typical signs of eutrophication (i.e., extreme nutrient levels), including intense algal blooms and periods of low dissolved oxygen levels (or hypoxia) or anoxia (Xia *et al.,* 2010). Other problems that result from coastal development include degraded benthic communities, a decrease in the extent of seagrasses, and the loss of functioning oyster reefs.

Topics of Scientific Debate and Uncertainty

Connectivity of the southwest Florida benthic offshore habitats to the estuaries and Florida Keys is likely but not well understood. Fish and invertebrate species (e.g., red drum, pink shrimp, stone crab) use the shelf and estuaries for part of their life cycle. Population genetics suggest that the estuaries may have subpopulations, but there are high rates of gene flow along the estuaries of the SWFS (Lester, 1979; Gold and Turner, 2002; McMillen-Jackson and Bert, 2004). A competitive grants program was recently initiated by NOAA/AOML to study the potential of deep water reefs to provide larvae and serve as a refugia for fish populations on the SWFS and Florida Keys (Palumbi, 2003). Circulation models support a north to south prevailing current pattern (Weisberg *et al.,* 2009), which translates into connectivity between biological communities on the SWFS, the Florida Keys, and Dry Tortugas.

There is currently no evidence that areas such as Pulley Ridge, or other critical fisheries habitats far from shore, are affected by stormwater runoff. There has been no evidence, to date, of hypoxic conditions affecting the broad SWFS in southwest Florida. The question remains, however, at what threshold of loading does a phase shift occur (Valiela *et al.,* 1997) where unusually large amounts of macroalgae out compete and smother benthic habitats and invertebrates, such as corals and pen shells. The scenario posed by Valiela *et al.* (1997) was applied to bays in Massachusetts where seagrass habitats (little to no stormwater runoff/loading) were displaced by macroalgae under moderate to high stormwater runoff/loading conditions. While not well documented, a period of above-average rainfall and tropical storm activity resulted in excessive macroalgal biomass near the tidal passes and on artificial reefs. As the macroalgae senesced or fragmented in storms, the macroalgae accumulated on barrier island beaches in unusual quantities. In a series of hydrodynamic modeling runs with a particle tracking model (Fugate, 2010), macroalgae from the mouths of the major river ended up in the nearshore environment and affected benthic offshore habitats. Other stormwater runoff from gulf-wide sources is poorly understood. The large plume and hypoxic zone is well documented in the northern Gulf of Mexico from the Mississippi River (Rabalais *et al.,* 1994).

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Habitat: Coastal Wetlands

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In a nutshell:

- Coastal wetlands form a critical ecotone at the boundary between freshwater and marine environments that help maintain water quality for the marine ecosystem and serve as a nursery and food source for many marine species.
- People value coastal wetlands because they stabilize the coastline and provide protection from storm surge and flooding, improve water quality by filtering nutrients, provide critical habitat for protected species, and provide aesthetic, recreational, and tourism value.
- In the barrier islands area, the coastal wetlands are threatened by development as mangroves and shorelines are replaced with an urban landscape. Throughout the southwest coastal region, anthropogenic changes in freshwater delivery are disturbing the salinity gradients necessary to maintain plant communities of the transition zone.
- The primary threats to the coastal wetlands are their vulnerability to impacts from sea-level rise and altered freshwater flow and changes in intensity and frequency of coastal storms.

Within the context of the SWFS ICEM, we have defined the coastal wetlands as the saltwater zone landward of the coastal margin, which includes the marshes, flats, and mangroves and the intermittent creeks, channels, and rivulets that flow through these areas (Figure 1). The entire region is characterized by gently-sloping topography with elevations less than a few meters above sea level (Zhang, 2011). The southwest coastal zone includes more than 148,263 acres of mangroves (Smith *et al.,* 1994), 400,300 acres of estuarine forested scrub-shrub (includes mangrove forests, dwarf mangroves, and buttonwoods), and 54,800 acres of salt marsh (primarily *Spartina* and *Juncus*) (Field *et al.,* 1991). NOAA's coastal wetlands inventory (Field *et al.,* 1991) lists the Ten Thousand Islands as having the largest extent of coastal wetlands of any estuarine drainage in the continental United States (2,165,000 acres). We have divided the southwest Florida coastal wetlands into four provinces (Figure 1) based on their dominant coastal features: Barrier Islands, Ten Thousand Islands, Everglades/Shark River Slough, and Cape Sable/White Water Bay. These provinces are, for the most part, very similar and are not specifically differentiated in the ICEM (Figure 2). There are, however significant differences in the attributes, drivers, and mechanism of change between the provinces. These differences are presented in cross-sectional transect figures for each region (Figures 3a-d).

The barrier islands are the most unique of the four provinces because they are extensively developed in comparison to the other provinces. In addition, they are characterized by beaches and wetlands dominated by herbaceous marshes, compared to the mangrove-dominated provinces to the

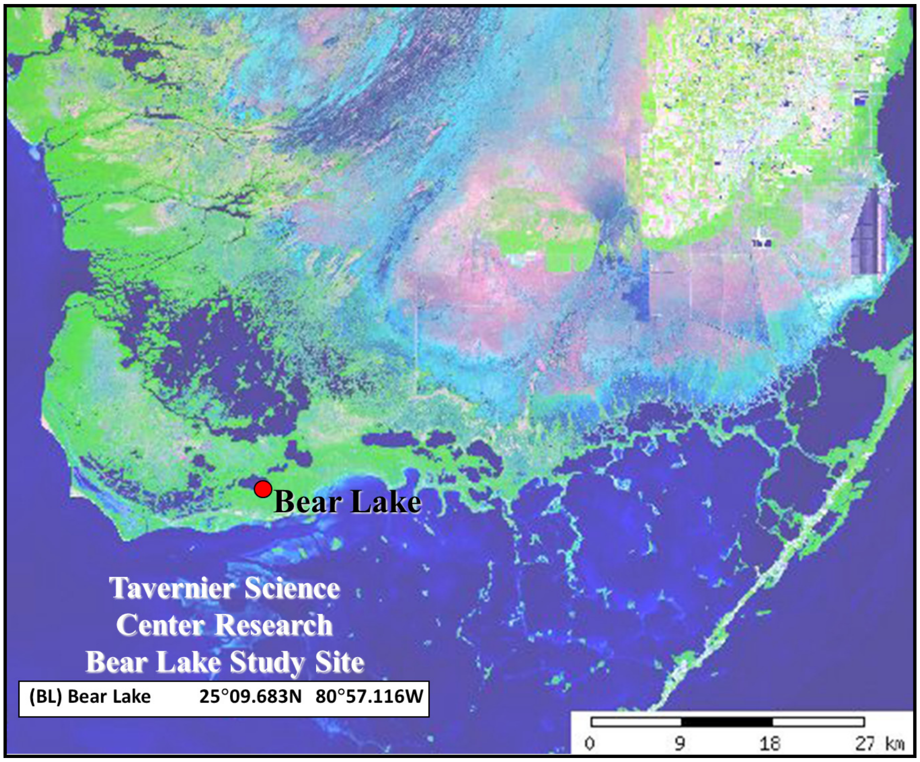

Figure 1. Map of the Southwest Florida Shelf subregion provinces. Note the Bear Lake study site in Cape Sable Province.

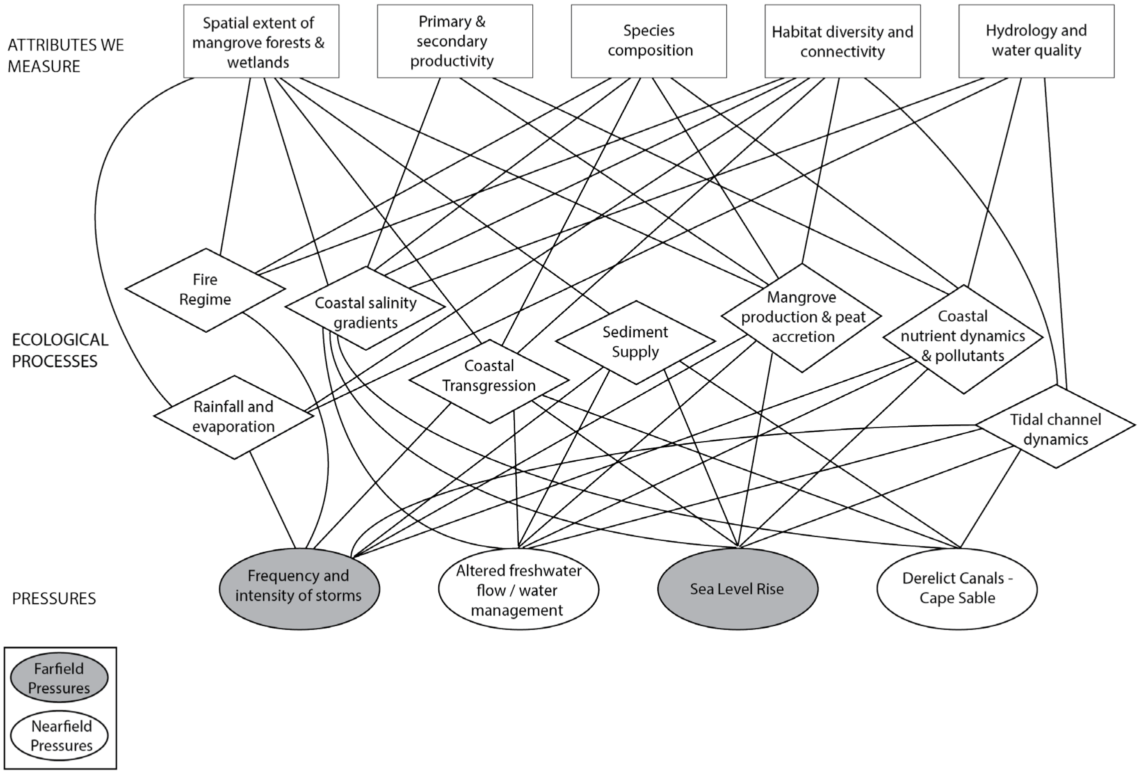

Figure 2. Coastal wetlands submodel diagram for the Southwest Florida Shelf.

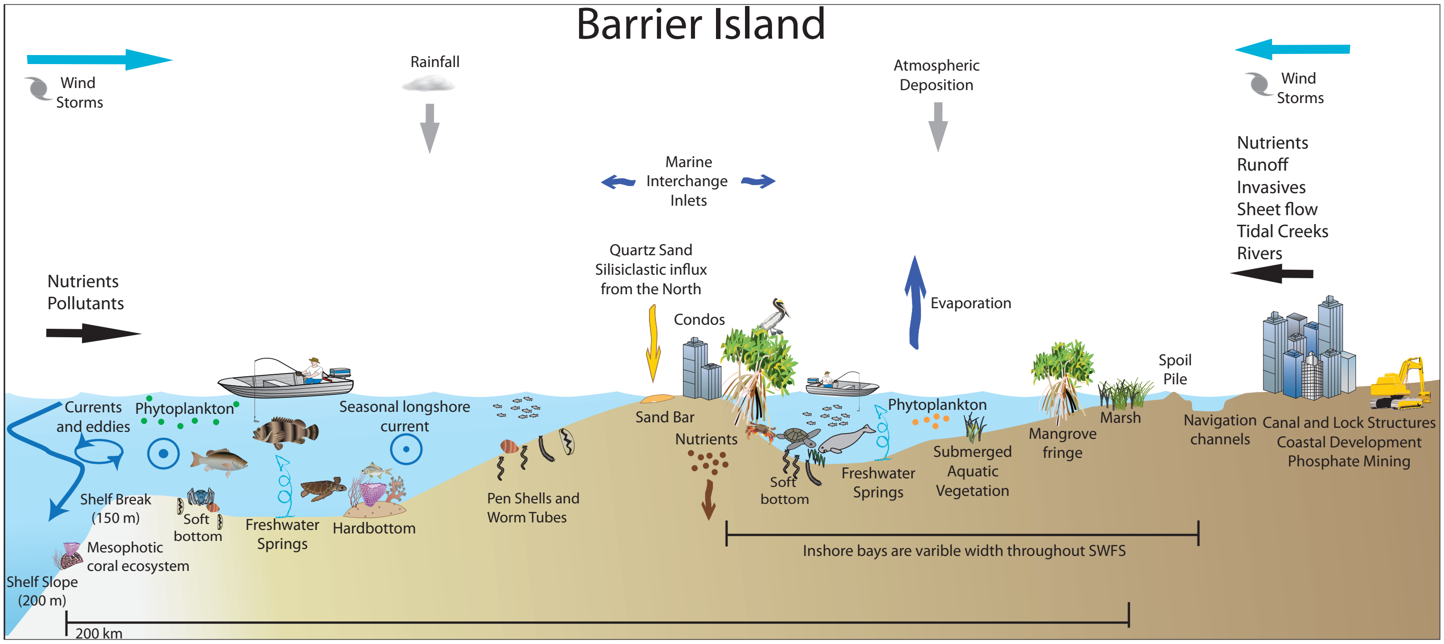

Figure 3a. Conceptual diagram of the Southwest Florida Shelf Barrier Islands Province ecosystem, processes operating upon it, and factors affecting its condition.

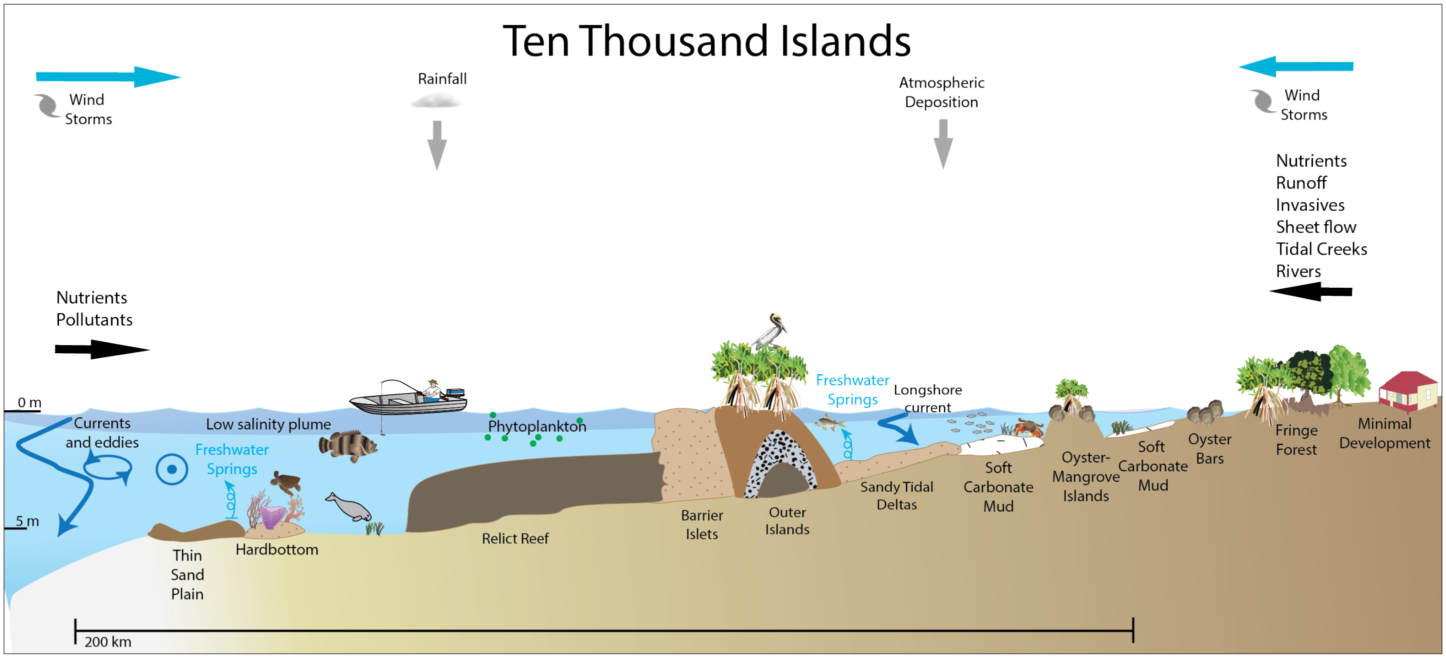

Figure 3b. Conceptual diagram of the Southwest Florida Shelf Ten Thousand Islands Province ecosystem, processes operating upon it, and factors affecting its condition.

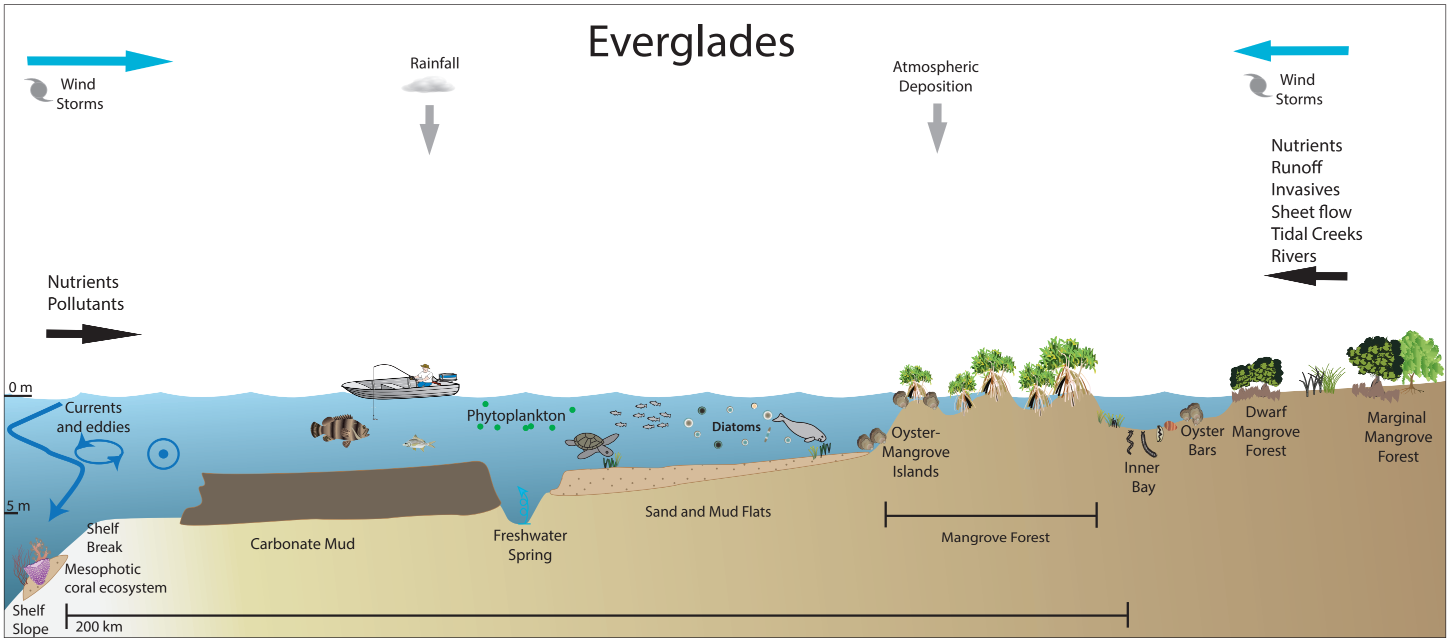

Figure 3c. Conceptual diagram of the Southwest Florida Shelf Everglades Province ecosystem, processes operating upon it, and factors affecting its condition.

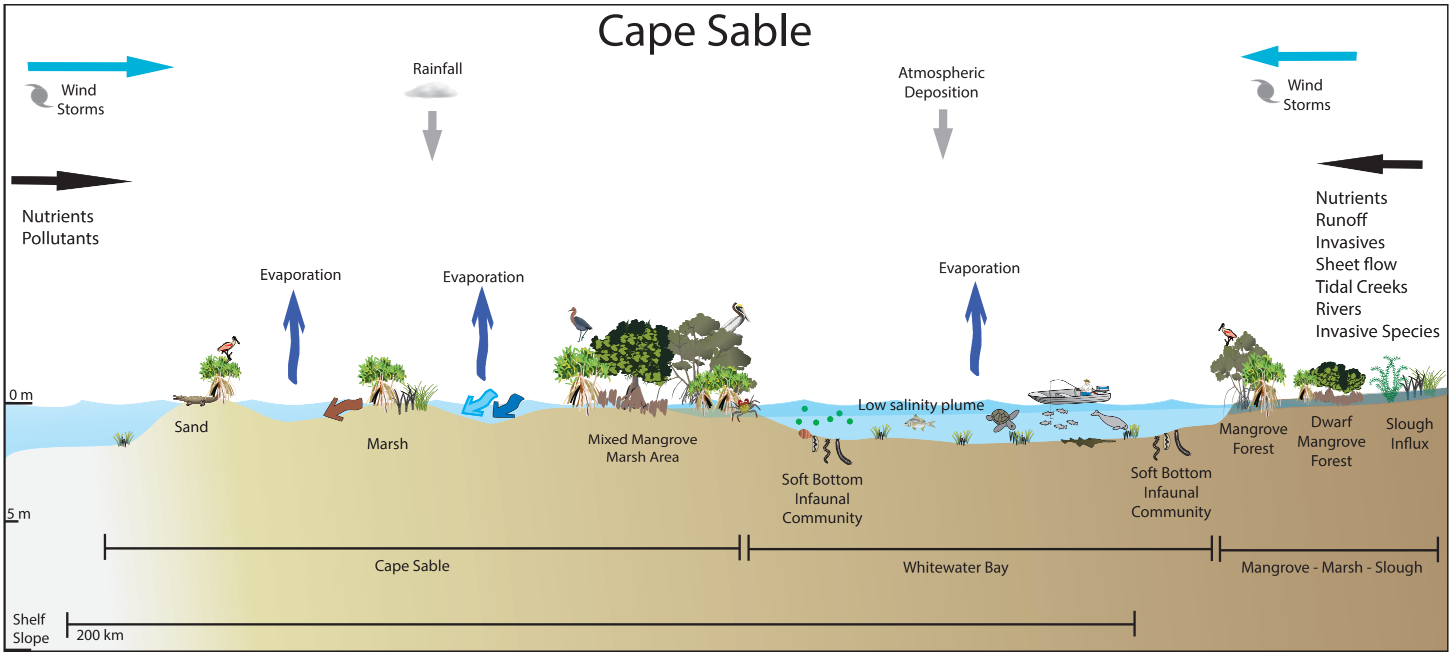

Figure 3d. Conceptual diagram of the Southwest Florida Shelf Cape Sable Province ecosystem, processes operating upon it, and factors affecting its condition.

south. The urbanization of this province has resulted in the destruction of wetlands, changes in water flow from the upland along with concurrent polluted runoff, stabilization of barrier islands, and greater demands on the environment in the form of increased fishing pressure and the extraction of groundwater to provide drinking water (Barnes, 2005). Besides direct urbanization in this province, the overall development of South Florida has led to large-scale changes in water management practices resulting in polluted water from Lake Okeechobee being discharged in much larger quantities than natural into the inshore bays through the Caloosahatchee River (Light and Dineen, 1994; Lodge, 2010; Barnes, 2005). This has resulted in algal blooms and red tides within the bays and red tides and blackwater events offshore (Barnes, 2005; Keller and Causey, 2005).

The Ten Thousand Islands, Everglades/Shark River Slough, and Cape Sable/White Water Bay provinces have been described by Davis *et al.* (2005, p. 832) as "a brackish water ecotone of coastal bays and lakes, mangrove and buttonwood forests, salt marshes, tidal creeks, and upland hammocks." The tidal range in this region is small (typically 0.3-0.6 m). The amount of freshwater flow from the Everglades is a significant factor distinguishing these three provinces. The Everglades region receives much more freshwater through Shark River Slough than the Ten Thousand Islands, which receives moderate flow from the Big Cypress Swamp, and the Cape Sable province, which receives little direct flow (except in Whitewater Bay; McVoy *et al.,* 2011; Schomer and Drew, 1982). The width of the mangrove zone in these areas can extend from 6-30 km inland (Zhang *et al.,* 2011). Dwarf mangrove forests are also a major component of the landscape in the Cape Sable/White Water Bay region. The Ten Thousand Islands province is distinguished by the numerous mangrove over-wash islands and tidal creeks. Abundant freshwater creeks and expanses of uninterrupted mature mangrove forests characterize the Everglades province (Shomer and Drew, 1982). Cape Sable is differentiated from the other two provinces by having extensive, seasonally-inundated mud flats in the interior, separated from the sand beaches along the exposed coastline by a narrow marl ridge that can reach about 0.8 m above sea level (Zhang *et al.,* 2011). It is separated from the Everglades province by Whitewater Bay (Shomer and Drew, 1982).

The coastal wetlands form a critical ecotone at the boundary between freshwater and marine environments and, thus, contain species from terrestrial, freshwater, estuarine, and marine environments at different points in their life cycles. Odum *et al.* (1982) reported that 220 species of fish, 21 reptiles, 3 amphibians, 18 mammals, and 181 birds use the mangroves of South Florida. The mangroves form the essential framework of this habitat. There are three species of mangroves in southwestern Florida: red (*Rhizophora mangle*), black (*Avicennia germanans*), and white (*Laguncularia recemosa*) (Lugo and Snedaker, 1974). 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 occurs within the mangrove forests (Ewel *et al.,*1998; Lugo and Snedaker, 1974). Epiphytes and sessile invertebrates frequently grow on specialized root adaptations of mangroves (prop roots and pneumatephores). These, plus the mangrove leaf litter, are the basis of mangrove food webs (Ewel *et al.,* 1998; Fry and Smith, 2002; Graneck *et al.,* 2009; Odum and Heald, 1975).

Role of the Coastal Wetlands in the Landscape

The coastal wetlands are particularly vulnerable to impacts from sea-level rise and changes in intensity and frequency of coastal storms. The IPCC (IPCC, 2007, p. 9) has identified coastal mangrove and salt marshes as environments that "are likely to be especially affected by climate change" due to "multiple stresses" associated with changing climatic patterns. Loss of the wetlands would have a profound effect on both the built and natural systems of South Florida because they provide tremendous functional, economic, and ecologic value including: (1) shoreline stabilization and storm protection; (2) flood protection; (3) water quality improvement through the filtering of nutrients; (4) critical habitat for wildlife and marine organisms, including threatened and endangered species in at least some stage of their life cycle; and (5) aesthetic, educational, sport, and tourist value (Field *et al.,* 1991; Odum *et al.,* 1982).

The southwest Florida coastal wetlands are highly productive. Small demersal fish and invertebrates (Heald *et al.,* 1984; Lorenz, 1999) are exploited by water bird species (Lorenz *et al.,* 2002; Odum *et al.,* 1982; Ogden, 1994; Powell, 1987) and game fish (Odum *et al.,* 1982; Odum and Heald, 1975) during relatively low water periods. These wetlands also provide critical nesting habitat for water birds (Kushlan and Frohring, 1985; Ogden, 1994) and nursery habitat for fishery species (Ashton and Eggleston, 2008; Comp and Seaman, 1985; Lewis *et al.,* 1988; Manson *et al.,*2005). In addition, these wetlands enhance the fish biomass on nearby seagrass beds (Manson *et al.,* 2005; Thayer and Chester, 1989), and oysters have been found to assimilate mangrove organic material (Surge *et al.,* 2003; Cannicci *et al.,* 2008). The mangroves, therefore, play a role in seagrass and oyster reef ecosystems. Furthermore, organic export from mangrove forests provides nutrients to surrounding ecosystems (Lugo and Snedaker, 1974; Odum and Heald, 1975; Twilley 1985, 1988; Nixon, 1980) but mangrove forests, depending on the type, can also sequester nutrients and act as a wastewater filter (Ewel *et al.,* 1998), thereby also playing a role in water quality.

Attributes People Care About

The mangroves and wetlands of the southwest Florida coast provide critical ecosystem services to the entire southwest coastal ecosystem including:

- Coastal erosion and storm protection
- Critical habitat for protected species and species recovery
- Wildlife viewing opportunities
- Recreational and commercial fishing
- Quality and aesthetics of the shoreline
- Environmental education and research
- Carbon sequestration
- Nutrient regulation and filtration for wastewater and stormwater runoff

Coastal Erosion and Storm Protection

Mangroves and coastal marshes are a natural barrier to shoreline erosion because the plants trap, hold, and stabilize sediments (Carlton, 1974; Estevez, 1998; Montague and Wiegert, 1990; Odum *et al.,* 1982). In addition, they mitigate the impact of waves and storm surges, providing protection to inland areas (Badola and Hussain, 2005; Montague and Wiegert, 1990; Odum *et al.,* 1982; Zhang *et al.,* 2011). Barbier *et al.* (2008), in a worldwide study, found that mangroves protected coastal communities from tropical storms up to 5 km inland. They also documented that there was an exponential decrease in wave height as the width of the mangrove zone along the coast increased. For salt marshes, they found a four-fold decrease in wave height with increasing distance inland (Barbier *et al.,* 2008).

Zhang *et al.* (2011) found that wind speed and the speed of progression of a storm are significant in determining the area of mangroves needed to protect a coastal zone. Even a narrow zone of mangroves can significantly reduce the impact of winds, but for storm surges the width of the mangroves must exceed 15-30 km to completely attenuate storm surge for slow moving category 4 and 5 storms (Zhang *et al.,* 2011). Model simulations based on observed storm surge effects along Florida's southwest coast indicate that without the presence of the mangroves the area of inundation would extend more than 70 percent further inland, causing significant damage to the areas inland from the mangroves (Zhang *et al.,* 2011).

Critical Habitat for Protected Species and Species Recovery

The characteristic plant species of the coastal wetlands form critical habitat area for a number of vertebrate and invertebrate species (Odum *et al.,* 1982), including 12 species listed by the U.S. Fish and Wildlife Service as endangered or threatened (Table 1, National Park Service; http://www.nature.nps.gov/biology/endangeredspecies/parksearch.cfm). The Florida Fish and Wildlife Conservation Commission's threatened and endangered list includes many more species than the federal list; however, the state's list was undergoing revision at the time of this writing so a complete list is unavailable. Other protected species that utilize this habitat are some fishery species (e.g., goliath grouper), marine mammals (e.g., bottlenose dolphin), and all migratory birds and wading birds. The wading birds are of particular interest, as they are iconic species of the region and are important indicators of Everglades restoration efforts. The three southern provinces contained wading bird colonies that in the early 1930s had an estimated 100 to 250 thousand nesting pairs of wading birds, but today these colonies only support several hundred to several thousand pairs (Ogden, 1994).

Wildlife Viewing Opportunities

Wildlife viewing activities contributed approximately $3.1 billion in retail sales to the Florida economy in 2006 with a total estimated economic effect of $5.2 billion (Southwick and Allen, 2008). It is estimated that southwest Florida has close to 2000 species of birds, fish, mammals, and other animals (Estevez, 1998). Viewing this diverse wildlife enhances the visitor experience for all tourists, even those who did not travel specifically to view wildlife. Travel specifically devoted to bird watching constitutes one of the largest wildlife viewing activities (Carver, 2009), and the coastal wetlands and mangrove forests of the southwest coast provide prime opportunities for viewing the diverse community of birds and other animals that utilize the habitat (Estevez, 1998; Montague and Wiegert, 1990; Odum *et al.,*1982). According to Carver (2009), waterfowl and birds of prey are the largest categories of birds watched away from the home, and these types of birds are abundant in the southwest coastal marshes. In addition, numerous species of birds use the wetlands as wintering or stop-over sites during their annual migration (Odum *et al.,* 1982).

Recreational and Commercial Fishing

Mangroves provide a critical habitat in the life cycle of many important commercial and recreational fishes as both shelter and detritus-based food source (Estevez, 1998; Heald *et al.,*1984; Lugo and Snedaker, 1974; Odum *et al.,* 1982). Important commercial and/or recreational species that rely on the mangrove-based food source include oysters, blue crabs, Caribbean spiny lobsters, pink shrimp, snook, mullet, menhaden, red drum, spotted sea trout, snapper, tarpon, ladyfish, jacks, and others (Odum *et al.,* 1982). Salt marshes also serve as important nursery and feeding grounds for estuarine animals (Montague and Wiegert, 1990).

Quality and Aesthetics of the Shoreline

Florida Statute 161.053 identifies beaches as "one of the most valuable natural resources of Florida." The barrier islands in Lee County include over 50 miles of beaches that are enjoyed by visitors and residents and provide a significant income from tourism (Murley *et al.,* 2003). In addition to these beaches, Cape Sable is lined by beaches designated as wilderness by the National Park Service and attracts "back country" visitors who wish to see pristine beaches in the absence of nearby urban areas. The salt marshes in this region provide a sense of wilderness (Montague and Wiegert, 1990) that is also valued by visitors and residents. The mangrove shorelines of the Ten Thousand Islands, Everglades, and Whitewater Bay regions provide a unique scenic vista for visitors to enjoy the myriad waterways and islands of the southwest coast while boating, fishing, or wildlife viewing (Odum *et al.,* 1982; Odum and McIvor, 1990). The mangrove coast from Flamingo (at the southeastern edge of the Cape Sable Peninsula) to Chokoloskee (northern end of the Everglades Province) is part of the largest wilderness area east of the Mississippi River. The intangible psychological value of the existence of such wilderness areas is difficult to quantify (Wegner and Pascual, 2011); even people who never visit this coast are inspired by photographs of the landscape and animals and place value in continued protection of this wilderness region (Montague and Weigert, 1990).

Environmental Education and Research

The coastal wetlands provide an opportunity to teach students and the general public about the environment and ecological concepts. The position of the wetlands at the transition between freshwater and marine environments provides an opportunity to examine the interaction between the adjacent environments (O'Neal, 1995) and learn about connections between the land and sea. The Rookery Bay Environmental Learning Center facility highlights this aspect of the coastal wetlands. This accessibility and confluence of environments also make the wetlands valuable areas for scientific research.

Carbon Sequestration

Coastal wetlands provide globally important carbon reservoirs, and the most carbon sequestration occurs in tropical and subtropical wetlands (Mitsch *et al.,* 2013). Twilley *et al.* (1986) estimate that the litter fall in fringing mangrove swamps of South Florida ranges between 1.86-12.98 metric tons ha^{-1} yr^{-1}. These environments sequester more carbon per unit area (averaging 210 g CO_2 m^{-2} yr^{-1}) than northern peatlands (averaging 20-30 g CO_2 m^{-2} yr^{-1}) and release less methane gas because of the abundant presence of sulfates (Chmura *et al.,* 2003). Although the coastal wetlands are a net sink for carbon, they do export organic matter to other marine systems (Ewel *et al.,* 1998; Odum *et al.,* 1982). Granek *et al.* (2009) demonstrated that filter feeders such as sponges, bivalves, and corals consume and assimilate mangrove-based organic matter when in proximity to mangrove forests.

Nutrient Regulation and Filtration for Wastewater and Stormwater Runoff

Mangroves and coastal marsh systems generally act as filters or traps for a number of elements, including nitrogen, phosphorus, trace elements, and heavy metals through combined interaction of the plants themselves, the soils, and the organisms that live there (Odum and McIvor, 1990; Estevez, 1998; Sklar and Browder, 1998). These elements may be stored in the wetlands for many years. This filtration reduces the amount of nutrients and potential pollutants entering the estuaries and marine system via runoff (Estevez, 1998; Sklar and Browder, 1998).

Attributes We Can Measure

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

- Spatial extent
- Habitat diversity and connectivity
- Primary and secondary productivity
- Species composition (including exotics)
- Hydrology and water quality

Spatial Extent

Remote sensing techniques, linked to strategic ground-surveying and geographic information systems analyses provide valuable assessment and management tools for understanding changes to the spatial extent of the coastal wetlands. The southwest coast of Florida ranks as the highest percentage of coastal wetlands in the country (Field *et al.,* 1991) and has the most extensive mangrove forest in the United States (Johnston *et al.,* 1991; Spalding *et al.,* 1997). This distribution is determined by the climate, geology, geography, and hydrography of the region. Because the majority of southwest Florida coastal wetlands are protected lands, this region has not suffered the significant declines seen on the east coast and in the Florida Keys due to land development (Spalding *et al.,* 1997). In fact, Krauss *et al.* (2011) have documented a 35 percent expansion of mangrove coverage in the Ten Thousand Islands province between 1927 and 2005, which they speculated may be due to rising sea level. This increase in mangroves, however, is causing a decline in the saltwater marshes, a habitat utilized by many foraging birds (Krauss *et al.,* 2011). It is important to monitor changes in distribution and spatial extent following storms and over the coming decades to determine responses to sea level-rise and climate change.

Habitat Diversity and Connectivity

In the coastal wetlands, the vertical habitat structure ranges from below the water surface in the muddy substrates of the creeks and inlets to the canopy of the forest. Moving inland from the water line, transitions occur from dense mangroves to open marshes; near the transition to freshwater, hardwood hammocks exist along the ecotone boundaries. For the aquatic habitats, salinity ranges from fresh to marine and from intermittent seasonal pools to persistent creeks and channels.

The connectivity of the sub-environments of the coastal wetlands to each other, and of the coastal wetlands to the upstream freshwater and terrestrial and downstream marine systems, is critical to the movement of organisms and the cycling of materials through the system (Odum *et al.,*. 1982). Movement of water through the system transports mangrove propagules and seeds, delivers nutrients, and flushes out sulfides and salts from the sediment pore water (Lugo and Snedaker, 1974; Odum and McIvor, 1990). The cycling of nutrients determines the productivity of the ecosystem with the most productive and well developed mangrove forests being located along the riverine systems delivering nutrients from the upland environments (Twilley *et al.,* 1986). Movement of the wetland detritus out into the creeks, inlets, and estuaries affects the productivity and biotic diversity of these aquatic systems (Odum and McIvor, 1990). Construction of canals, diversion of water, and upland drainage or impoundment impacts the coastal wetlands by altering the flow of materials and forming physical barriers to migration (Carter *et al.,* 1973; Davis *et al.,*2005; Lugo and Snedaker, 1974).

Primary and Secondary Productivity

Measurements of primary productivity can be made using gas exchange, litter fall, changes in tree diameter, or other methods (Odum *et al.,* 1982; Twilley *et al.,* 1986), and provide a means of assessing the health of the wetlands and determining if changing pressures are affecting their ecological responses. Mangroves are among the world's most productive ecosystems compared to other forests, wetlands, and agricultural systems (Odum *et al.,* 1982; Odum and McIvor, 1990). Forest type, tidal exchange (including movement of water through the soil and root systems), salinity of the water, and nutrient availability are key factors in determining mangrove productivity (Carter *et al.,*1973; Lugo and Snedaker, 1974; Odum *et al.,* 1982; Twilley *et al.,* 1986). Measurements of net primary productivity in several locations in the southwest coastal zone range from 2.8 gC/m^2/day for a red mangrove forest to 7.5 gC/m^2/day for a mixed stand of red, black, and white mangroves (Lugo and Snedaker, 1974). Higher rates of net primary productivity are reported in coastal areas that are frequently well-flushed and that are exposed to higher nutrient concentrations (Lugo and Snedaker, 1974), but other studies indicate this response is dependent on species type and a number of other variables (Odum *et al.,* 1982; Odum and McIvor, 1990; Twilley *et al.,* 1986).

Biomass is one measure of organic production in the mangrove ecosystem, and it can be a useful tool for comparing systems; however, many variables affect biomass (Carter *et al.,* 1973; Lugo and Snedaker, 1974; Odum *et al.,* 1982), and estimates of biomass in mangroves often exclude the root structures (Odum and McIvor, 1990). Different species of mangroves partition biomass very differently, and their responses are affected by a number of factors including age of the forest, stand history (e.g., hurricane impacts), structural differences, tidal transport, nutrients, etc. (Lugo and Snedaker, 1974; Odum *et al.,* 1982).

The mangrove forests are a critical component of estuarine productivity in the southwest coastal zone beginning with the introduction of detritus into the system (Carter *et al.,* 1973; Odum and McIvor, 1990). Changes in the net primary production of the ecosystem can have significant impacts on the secondary productivity of the system (Carter *et al.,* 1973). Reduction in detrital output reduces invertebrate, foraging fish, predatory fish, and bird populations as the impacts are felt up the food chain (Carter *et al.,* 1973). In addition, because the coastal wetlands serve as a nursery for many marine species, the impacts are felt beyond the immediate community (Lugo and Snedaker, 1974). Species such as the pink shrimp (*Farfantepenaeus duorarum*) and many sport and commercial fish are directly affected by the productivity of the coastal wetlands (Lewis *et al.,*1988).

Species Composition (Including Exotics)

The coastal wetlands contain a mixture of mangrove species along with varying occurrences of emergent (e.g., *Eleocharis* spp. and sawgrass) and submerged (e.g., manatee grass and Chara) aquatic vegetation (e.g., Lugo and Snedaker, 1974). The structure and dynamics of the habitat are determined by the mix of plant communities (Lugo and Snedaker, 1974; Odum and McIvor, 1990) which, in turn, influences the composition of invertebrate and vertebrate assemblages. The prop roots of the red mangroves (*Rhizophora mangle*) provide habitat for numerous invertebrate and fish species, including juvenile Caribbean spiny lobsters (*Panulirus argus*) and pink shrimp (Odum *et al.,* 1982; Kaplan, 1988). The infrequently flooded zones of the black mangrove forest are inhabited by fish specifically adapted to tolerate these extremes (Odum *et al.,* 1982). The canopy of the mangrove forest provides extensive nesting opportunities for passerine and non-passerine birds, and the diverse environments of the coastal wetlands attract wading birds, surface feeders, and divers. Utilizing the forest floor and channels are the larger organisms, the reptiles and mammals that feed on all the diverse fauna and flora present in the system. Twelve

Table 1. Species listed as either threatened or endangered by the U.S. Fish and Wildlife Service that utilize the southwest Florida wetlands according to the National Park Service.

American crocodile	*Crocodylus acutus*	Threatened
Bald eagle	*Haliaeetus leucocephalus*	Delisted Monitored
Garber's spurge	*Chamaesyce garberi*	Threatened
Green sea turtle	*Chelonia mydas*	Endangered
Hawksbill sea turtle	*Eretmochelys imbricata*	Endangered
Kemp's Ridley sea turtle	*Lepidochelys kempii*	Endangered
Leatherback sea turtle	*Dermochelys coriacea*	Endangered
Loggerhead sea turtle	*Caretta caretta*	Threatened
Piping plover	*Charadrius melodus*	Threatened
Roseate tern	*Sterna dougallii dougallii*	Threatened
Smalltooth sawfish	*Pristis pectinata*	Endangered
West Indian manatee	*Trichechus manatus*	Endangered
Wood stork	*Mycteria americana*	Endangered

vertebrate species listed by the U.S. Fish and Wildlife Service as endangered or threatened use the coastal wetlands of southwest Florida (Table 1).

Disturbances in the habitat structure caused by sea-level rise, changes in freshwater supply, fire, storms, or other factors provide opportunities for invasive species to become established in the environment. The direct impacts of these invasive plant and animal species on the coastal wetlands are not well understood, but a study of invasive plant species in Florida has found that they can alter the geomorphology, hydrology, biogeochemistry, and community composition of an area (Gordon, 1998).

Exotic plants in the coastal wetlands include Brazilian pepper (*Schinus terebinthifolius*), Asian nakedwood/lather leaf (*Colubrina asiatica*), Australian pine (*Casuarina equisetifolia*), and many others (CISMA, 2009), and it is important to monitor changes in their distribution and abundance. Brazilian pepper is becoming particularly problematic; in the entire greater Everglades ecosystem it expanded from ~37,000 acres to ~57,000 acres between 2005 and 2008 (CISMA, 2009). Old world climbing fern (*Lygodium microphyllum*) is increasing in the coastal wetland areas. Because of its ability to spread rapidly, it can smother whole communities of plants (SFWMD, 2003). Along the coastline of Biscayne Bay, several exotic species of Indo-Pacific mangroves are expanding and, because of the dispersion methods and low plant diversity of the native Florida mangroves, the potential exists for more widespread invasion (Fourqurean *et al.,* 2009). Disturbances such as fire, storms, water impoundment, or changes in freshwater flow provide opportunities for non-native plants to expand in the coastal wetlands (Gunderson, 1994; Fourqurean *et al.,* 2009; Smith *et al.,* 1994; Thomas and Rumbold, 2006).

Exotic invertebrates may become an increasing problem in the future as conditions in the coastal wetlands change. The red-rimmed melania snail (*Melanoides tuberculatus*) has been found in the dwarf mangrove region in the Whitewater Bay area (Wingard *et al.,* 2009). This species is native to southeast Asia, but has been found in South Florida since 1971 (Russo, 1973). It can be harmful to human populations and animal populations because of a number of parasites that use the species as a host (Wingard *et al.,* 2008). A concern for the region is that although it is a freshwater species in its native habitat, it has been adapting to estuarine conditions in South Florida (Wingard *et al.,* 2008; Murray *et al.,* 2010). As temperatures increase over the next century, this species may expand its range and compete for resources with the native snail populations and may become a vector for human and wildlife diseases.

Hydrology and Water Quality

Coastal wetlands are influenced strongly by the quantity and quality of water available. Hydrologic parameters are monitored throughout the coastal wetlands provinces by an array of automated hydrostations, many of which are telemetered and provide real-time data. Typically, these hydrostations collect water level, salinity, temperature, and rainfall. Some also collect flow volumes using Doppler radar technology (http://waterdata.usgs.gov/nwis/qwdata?). Water level in the coastal wetlands is controlled by several factors and follows a stereotypic annual cycle as presented in Figure 4 (Robinson *et al.,* 2011). These data and the salinity data were collected using a Hach brand sensor and a Campbell brand recorder by J.J. Lorenz (unpublished data). Collection methods and quality control standards followed those of Lorenz (1999) and Lorenz and Serafy (2006).

Starting with the wet season in June, water levels increase throughout the summer months, peaking in late September or early October. Water levels typically decline through October and November, culminating in dry season conditions from January through April or May. One underlying cause of this cycle is seasonal changes in sea surface elevation caused by thermal expansion of the Gulf of Mexico during summer months and subsequent contraction during the winter (Marmar, 1954; Stumpf and Haines, 1998). Rainfall patterns are also seasonal, with 60 percent of the rainfall occurring from June to September and only 25 percent from November through April (Duever *et al.,* 1994), thereby augmenting the underlying water level cycle caused by sea surface elevation. Tropical weather systems and strong winds associated with cold fronts during winter months can cause short-term changes in water levels through wind-driven tides (Holmquist *et al.,* 1989). Wetlands closer to the Gulf of Mexico also experience changes in water level on a twice daily cycle through diurnal tides, while more isolated wetlands (e.g., the interior wetlands of Cape Sable and Shark River Slough) may not experience diurnal tides at all. Finally, water management practices can result in pulsed increases in water levels at a regional spatial scale due to the opening and closing of canal structures (Lorenz, 2000).

The annual salinity cycle in the coastal wetlands is inextricably linked to the water level cycle and follows a similar but inverted pattern (Figure 5; Robinson *et al.,* 2011). Salt concentrations are typically highest in late May or early June and rapidly decline with the onset of the wet season (Jiang *et al.,* 2011). With the exception of relatively brief pulses in salinity in the early wet season (that usually only occur in dry years), salinity remains low throughout the wet season and is typically at its annual minima from September through December. Salinity begins to pulse upward in December and typically a steady and sustained increase begins in January or February that continues through to the beginning of the wet season. The data in Figure 5 were collected at a hydrostation in the interior wetlands of Cape Sable, a region that is largely isolated from direct influence

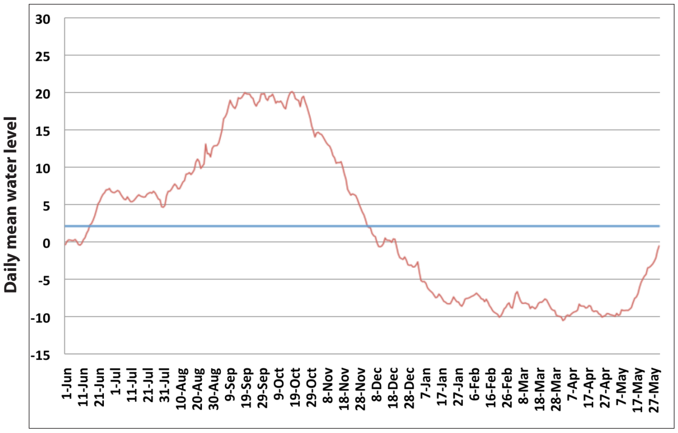

Figure 4. Annual water level cycle at Bear Lake (Figure 1) on Cape Sable for an averaged hydrologic year (June-May). Data are in centimeters and are relative to the ground level of the surrounding ephemeral wetlands such that zero represents the water depth at which these peripheral seasonal wetlands become dry. The daily mean water level was calculated from a 20-year period of record (1990-2010). The horizontal line represents overall mean water level for the period of record. Adapted from Robinson *et al.* (2011).

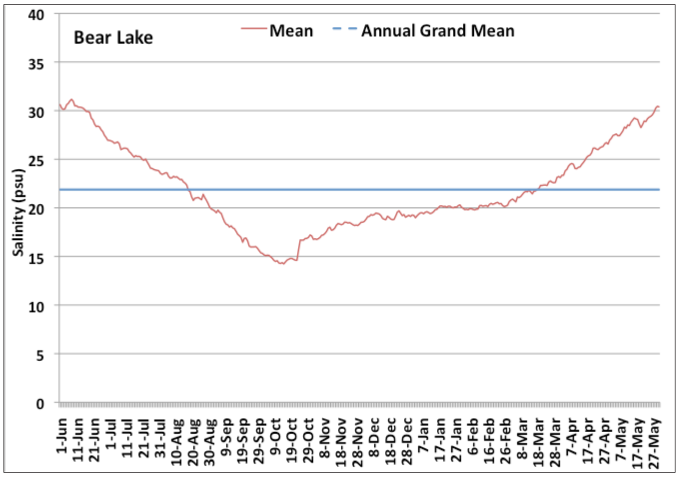

Figure 5. Annual salinity cycle at Bear Lake on Cape Sable for an averaged hydrologic year (June–May). The daily mean water level was calculated from a 10-year period of record (2000-2010). The horizontal line represents overall mean water level for the period of record. Adapted from Robinson *et al.* (2011).

of diurnal tides or water management influences. Although Figure 5 shows an example of the stereotypic annual salinity, the cycle itself varies from location to location based on the proximity to marine and freshwater influences. For example, mean salinity will be relatively low and the variability higher in areas closer to a freshwater source, while mean salinity will be relatively high and variability dampened when in proximity to the marine environment (Lorenz, 1999; Lorenz and Serafy, 2006).

Typically measured water quality parameters include monthly measurements of salinity, temperature, dissolved oxygen, pH, total phosphorus (TP), total nitrogen (TN), total organic carbon (TOC), nitrate (NO_3), nitrite (NO_2), ammonium (NH_4), soluble reactive phosphorus (SRP), and chlorophyll-a. Water samples are generally collected by shipboard grab samples (in bottles) along a defined transect; however, there are some water quality platforms that collect bottled samples at pre-defined intervals and then the samples are analyzed for a subset of water quality parameters when the platforms are serviced. The shipboard grab samples are collected in deeper and more open areas of the coastal wetlands and adjacent marine environment, while the platforms can be placed in more constrained areas such as narrow creeks and shallow basin forests. Water quality samples are analyzed by standardized methods (Boyer and Briceño, 2008) for the appropriate parameters based on how the data were collected. Through 2008, shipboard samples were collected systematically throughout all four provinces (Boyer, 2006). These data indicate that total phosphorus ranges from 0.005-4.02 µM and total nitrogen from 1.5-213 µM. The magnitude of these ranges is indicative of the innate variability within the ecosystem, as well as differences in land use across the region (Boyer, 2006). Table 2 provides the ranges of other water quality parameters.

Comparison of medians and variability of parameters among classes allowed large-scale generalizations as to the underlying differences in water quality in these regions of southwest Florida (Boyer, 2006). A strong gradient in estuaries from high nitrogen-low phosphorus in the south to low nitrogen-high phosphorus in the north was ascribed to marked differences in land use, freshwater input, geomorphology, and sedimentary geology along this tract (Boyer, 2006). These nutrient gradients are believed to be the result of changes in coastal geomorphology and watershed characteristics across the region (Boyer, 2006).

Table 2. Median, minimum, and maximum values for the most common water quality parameters (source: J. Boyer, Plymouth State University).

Variable	Median	Minimum	Maximum	n
Salinity (psu)	16.2	0.0	42.8	6299
Temperature (°C)	26.9	12.3	38.4	6280
DO (mg l^{-1})	5.8	0.3	24.4	6279
NO_3^- (µM)	0.66	0.01	19.17	6302
NO_2^- (µM)	0.16	0.005	9.94	6302
NH_4^+ (µM)	1.06	0.01	74.68	6302
TN (µM)	36.85	1.51	213.47	6299
TP (µM)	0.81	0.005	4.02	6287
SRP (µM)	0.086	0.001	2.138	6291
CHLA (µM)	2.93	0.11	45.11	6300
TOC (µM)	946.9	38.2	5334	6281
$Si(OH)_4$ (µM)	59.25	0.1	228.57	1668
Turbidity (NTU)	3.97	0.06	107.81	6299

Another important factor influencing the water quality of the region is the geological setting. Sediments in the southern region are composed of carbonates but change to siliceous quartz sand around Cape Romano (Gleason *et al.,* 1984). The process of biogenic carbonate formation acts to scavenge phosphorus from the water column (Bosence, 1989). Therefore, the more northern estuaries would be expected to be less phosphorus-limited than the southern. The ecological significance of these gradients is germane to effects of future hydrological restoration plans.

Odum *et al.* (1982) characterized the water quality of mangrove systems in Florida as "low micronutrient concentration (particularly phosphorous); relatively low dissolved oxygen and frequently increased water color and turbidity." They also indicated that these parameters were highly variable both temporally and spatially. These same characteristics apply to the broader scale of most coastal wetlands on the southwest coast of Florida (Davis *et al.,* 2005; Barnes, 2005; Boyer, 2006). Historically, freshwater entering the coastal wetlands from the Everglades was very low in nutrients (Noe and Childers, 2007), and much of the nutrient load in the coastal system was provided by the marine environment through diurnal and wind-driven tides (Davis *et al.,* 2005; Childers *et al.,* 2006). Agricultural runoff, urban storm water runoff, and water management practices have altered this condition upstream in the freshwater wetlands (Noe and Childers, 2007) and presumably are impacting portions of the coastal wetlands. The best example of this is the discharge of nitrogen and phosphorus-rich water from the Peace River to Charlotte Harbor, which is correlated with algal blooms, red tide, and blackwater events that have had profound effects on higher trophic levels on the SWFS (Heil *et al.,* 2007).

Pesticide, herbicide, and pharmacological residues, as well as petroleum-based compounds, have been measured in these coastal wetlands (Rand and Gardinali, 2004; Carriger and Rand, 2008), but there is no long-term systematic sampling for these contaminants. The effect of these pollutants on the coastal wetland ecosystem is little understood but, given the common use of these products on nearby uplands, there are likely to be measurable impacts.

Drivers of Change in the Coastal Wetlands

Climate, sea level, and bedrock geomorphology shaped the evolution of the southwest Florida coast over the last 7000 years (Wanless *et al.,* 1994; Willard and Bernhardt, 2011). As rates of sea level rise decreased about 3000 years ago, the coastline stabilized, and the mangrove coast of today began to form (Willard and Bernhardt, 2011). During the 20th century, however, land use and water management practices have altered the movement of freshwater into the system and disrupted the balance between terrestrial and marine processes (McIvor *et al.,* 1994). The primary drivers of change that will affect the coastal wetlands in the coming decades and centuries are water management practices and global climate changes (Davis *et al.,* 2005). The coastal transition zone represents a region where sustainability is dependent upon a balance of forces, including climate, tidal fluctuation, runoff of freshwater and terrestrial nutrients, substrate, and wave energy (Odum and McIvor, 1990). Global climate models suggest significant increases in the rate of sea-level rise over the next 100 years (Allison *et al.,* 2009; IPCC, 2007; Twilley *et al.,* 2001). Rising sea level will affect the distribution of coastal ecotones and may result in a loss of coastal wetlands (Krauss *et al.,* 2011; Wanless *et al.,* 1994). In the Barrier Islands Province, development will prevent inland migration and, in the Ten Thousand Islands Province, the islands will likely disappear.

The faster the rate of sea-level rise, the less likely the mangrove forests and salt marshes can keep pace with the change (Wanless *et al.,* 1994). Sea-level rise will also make the coastal wetlands more vulnerable to the impacts of storms, which may be more intense and more frequent in the future (IPCC, 2007). Land use and water management practices can either contribute to the pressures of global climate change or can help alleviate some of the impacts (Wanless *et al.,* 1994).

Description of Pressures

Altered Freshwater Flow – Quantity and Timing

Landscape alterations and water management practices that change natural flow patterns are one of the primary drivers in coastal ecosystems (Davis *et al.,* 2005; Sklar and Browder, 1998). The balance between salt water influx from the marine systems and freshwater flow from the terrestrial systems defines the transitions within any coastal wetland environment. A 59 percent reduction in freshwater flow during the 20th century due to water management practices is indicated by an analysis of coral florescence (Smith *et al.,* 1989), and a model based on paleosalinity estimates indicates freshwater flow was 2.5-4 times greater prior to 1900 compared to the late 20th century (Marshall *et al.,* 2009). Changes in flow cause a cascade of changes to other key physical components of the ecosystems, including water depth, salinity, nutrients, and dissolved oxygen which, in turn, cause changes in biological components such as productivity, community structure, and species composition (Sklar and Browder, 1998). Altered freshwater flow patterns also have damaging consequences to eastern oysters (*Crassostrea virginica*) and, therefore, the entire oyster reef ecosystem (Volety *et al.,* 2009).

Primary and secondary productivity of the entire system is affected by nutrients carried in the freshwater runoff. In the southwest coastal area of the Everglades, the altered freshwater regime delivers relatively high nutrient loads and has altered the hydroperiods, stimulating productivity and leading to the invasion of opportunistic native plants and invasive exotics (Sklar and Browder, 1998). Childers *et al.* (2006) found that reduced freshwater flow was associated with higher total phosphorus in the Shark River Slough mangrove estuaries. Volume of flow also is critical to productivity. There is an optimum flow level, below which nutrient deficiencies and soil oxidation can occur and above which abrasive flows and waterlogging of the wetlands can occur (Sklar and Browder, 1998).

Sea-Level Rise

The marshes and mangrove forests of the southwest coastal area of Florida developed and stabilized during the last 3000 years (Willard and Bernhardt, 2011), a period of relatively slow rates of sea-level rise averaging approximately 4 cm per century in the region (Wanless *et al.,* 2000). Since 1930, however, this rate has accelerated to approximately 20-40 cm per century (Wanless *et al.,* 1994), which has led to a destabilization of the coastline. As the marine waters transgress into the marshes and mangroves, the ecotones shift landward (Wanless *et al.,* 2000; Krauss *et al.,* 2011; Jiang *et al.,* 2011).

Model results suggest that the global rate of sea-level rise may accelerate further in the 21st century. The IPCC 2007 projections for worldwide sea-level rise range from 20-60 cm during the 21st century; however, these rates do not include factors such as ice sheet flow dynamics that could significantly increase the rate. The more recent Copenhagen Diagnosis (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. The Copenhagen Diagnosis states that "for unmitigated emissions [sea level rise] may well exceed 1 meter" by 2100, with an upper limit at approximately 2 meters.

Frequency and Intensity of Storms

The effects of hurricanes and their associated storm surges on mangroves and marshes have been studied following hurricanes Andrew in 1992 and Wilma in 2005. The combination of wind and storm surges have caused substantial die-off in the mangrove forests of the southwest Florida coast with a number of related effects, including increased erosion due to uprooting of the trees, increases in carbon and nutrients released into the waters, and repopulation of denuded areas by invasives (Smith *et al.,* 1994, 2009; Wanless *et al.,* 1994). Wanless *et al.* (1994) suggested that future "major hurricanes will cause dramatic steps of erosion, as well as overstepping of coastal wetland margins," because mangrove propagules are unable to take hold in the newly deepened erosional surfaces. These areas become intertidal mud flats, which may remain barren for years (Wanless *et al.,* 1994) and, with rising sea level, will likely be converted to shallow estuarine environments (Smith *et al.,* 2009).

The IPCC Summary Report for Policymakers (2007, p. 12) states that "it is likely that future tropical cyclones (typhoons and hurricanes) will become more intense, with larger peak wind speeds and more heavy precipitation associated with ongoing increases of tropical SSTs" [sea surface temperatures]. Models predict that rising tropical sea surface temperatures can lead to an increase in the number and intensity of tropical storms in the North Atlantic (Mann *et al.,* 2009), and an increase of 1°C in global sea surface temperatures results in a 30 percent increase in category 4 and 5 storms worldwide (Elsner *et al.,* 2008). The Copenhagen Diagnosis (Allison *et al.,* 2009) discusses evidence of increased hurricane activity over the past decade and a global increase in the number of category 4 and 5 hurricanes. Such an increase in frequency and intensity of storms would accelerate losses of the coastal wetland environments of southwest Florida in the coming century.

Increases in the frequency of thunderstorms, particularly in the tropics and southeastern United States, also have been predicted in association with increased atmospheric temperatures (Trap *et al.,* 2007; Aumann *et al.,* 2008). In addition to wind and rainfall, thunderstorms play a role in fire generation in South Florida (Gunderson and Synder, 1994), and southwest Florida currently has one of the highest incidences of lightning strikes in the Unites States (Michaels *et al.* 1987). Given this combination of effects of increases to air and ocean temperatures, these factors have an indirect affect on the coastal wetlands of southwest Florida.

Man-Made Channels

Construction of canals and hardening of creek banks has a significant impact on coastal wetlands because it can cause ponding or impoundment behind the barriers, restricting sediment influx to the marshes and mangroves and promoting subsidence and saltwater intrusion (Sklar and Browder, 1998). Estevez (1998) discusses the impact of the channelization of the Caloosahatchee on Charlotte Harbor and the delivery of pulses of freshwater into the system.

The Cape Sable/Whitewater Bay Province is also affected by man-made channels. The interior wetlands of Cape Sable were historically isolated from the Gulf of Mexico, but early in the last century, five canals were dug through the marl ridge to drain and reclaim land for development, agriculture, and cattle grazing (Will, 1984). Historically the wetlands interior of these canals were freshwater (Allen, 1947; Will, 1984). By the 1950s, however, the wetlands were converted to open water and mangrove habitats by salt water intrusion through the canals, which was exacerbated by storm surges (Wanless and Vlaswinkel, 2005). All five of these canals were subsequently plugged with earthen dams during the late 1950s and early 1960s (Wanless and Vlaswinkel, 2005). In the late 1990s, two of these dams were breached and tidal forces expanded the canals from 5-7 m wide and less than 0.5 m deep to about 20 m wide and 3 m deep (Wanless and Vlaswinkel, 2005).

The resulting tidal exchange moved enough sediment from the interior wetlands on Cape Sable to accumulate sediment in Lake Ingraham at rates as high as 15 cm per year, resulting in nearly half of Lake Ingraham being filled to the low tide mark on the seaward side of the canals (Wanless and Vlaswinkel, 2005). Furthermore, these canals are believed to have degraded biological productivity of the interior wetlands. Dams on these two canals have been replaced with 100-foot thick steel and earthen structures; however, a third canal at the north end of Lake Ingraham failed in November 2007, probably as a result of damage sustained two years earlier during hurricanes Katrina and Wilma (Lorenz, personal observations and photographs). Two separate efforts were made to repair the breach but in late fall of 2009 the last repair failed. This canal is now as large as the two that were plugged. Earthen dams on the other two canals have also eroded over the years and water was observed seeping through one of these dams in August 2009. Unless measures are taken to plug the northern canal and bolster the two remaining dams, the damage to both the interior of Cape Sable and the exterior embayments will continue.

Mechanisms of Change: Description of Ecological Processes

Climate change and associated sea-level rise are the most ubiquitous mechanisms of change. These drivers affect fire regime, rainfall accumulation, coastal salinity gradients and transgression, sediment supply, peat accretion, coastal nutrient dynamics, and tidal channel dynamics. Other drivers that influence these mechanisms of change include water management, stormwater runoff, urban development, tropical storms, and channelization not associated with water management.

Fire Regime

There are two sources of fire ignition: humans and lightning strikes. A number of factors including vegetation characteristics, biomass, surface water, soil moisture conditions, wind speed and direction, humidity, and rainfall control the extent and duration of a fire (Gunderson and Snyder, 1994). Natural fires are most common in the summer months due to an increase in lightning strikes (Duever *et al.,* 1994; Hofstetter, 1984), but they tend to be more widespread at the beginning of the wet season (April or May) when the region is still dry and the lightning storms are just beginning. Wade *et al.* (1980) has correlated increased development with altered patterns and frequency of fires in nearby undeveloped areas. For the coastal wetlands, the human development factor is particularly important in the Barrier Islands area, somewhat in the Ten Thousand Islands, and much less so to the south.

Fires play an important role in the ecosystem. In the mangrove forests and marshes of the coastal wetlands, fires can result in subsidence by affecting the rates of peat accretion either by removing materials that will contribute to the peat or by directly burning the peat in the case of extreme fires (Davis *et al.,* 2005; Smith *et al.,* 1994). The altered landscape following the fire can provide an opening for invasives to take hold in the landscape or for a different native flora to move in (Gunderson, 1994). Conversely, periodic fires clear out dense shrubs, deterring succession and creating open areas where graminoid marshes can form (Hofstetter, 1984). In the case of the invasive *Lygodium*, the plant can actually alter the effects of a fire because the thick mats of the climbing fern blanket entire areas from the canopy down to the understory, allowing what normally would have been "ground fires" to jump up into the canopies, killing off trees that would have survived (SFWMD, 2003).

Rainfall and Evaporation

Seasonal patterns of rainfall and evaporation are an integral part of the South Florida ecosystem (Duever *et al.,* 1994) and, although the impact of seasonal rainfall has been greatly altered by water management practices, the regional weather patterns still play a key role in the balance between the freshwater/saltwater interface in the coastal wetlands (Jiang *et al.,* 2011; McIvor *et al.,* 1994; Shomer and Drew, 1982). The IPCC 2007 report indicates that there will be a likely decrease in precipitation in subtropical land regions over the next century, but the relationship between overall precipitation and precipitation associated with the increased likelihood of hurricanes and changes in atmospheric temperature is unclear (Scavia *et al.,* 2002). Predicted increases in global temperatures (IPCC, 2007; Allison *et al.,* 2009) will lead to increased evaporation rates. Less rainfall and increased evaporation rates, combined with rising sea level discussed above, indicates there will be less freshwater available to the southwest Florida coastal wetlands in the future.

Coastal Salinity Gradients

Coastal salinity is a balance between the influx of freshwater through the canals, wetlands, and river systems, rainfall, and the marine processes. Wind, tides, and currents can drive marine water into the rivers, bays, and wetlands, leading to salinity increases (Jiang *et al.,* 2011), while storms and releases of freshwater by water management can lower salinity. Canals can lead to salt water intrusion further inland, thereby expanding salt marshes and mangroves further inland (Wanless and Vlaswinkel, 2005) or changing the composition of the ecotones (Krauss *et al.,* 2011).

Coastal Transgression

Predicted rising sea levels will greatly alter the type and spatial extent of the coastal wetlands (IPCC, 2007; Jiang *et al.,* 2011; Wanless *et al.,* 1994; Wanless *et al.,* 2000). Wanless *et al.* (1994) indicate that wetland soil accretion is unlikely to keep pace with the rate of sea-level rise. Tropical storm winds and storm surges will likely destroy mangroves (and presumably other vegetation). With higher sea surface elevation, the establishment of new seedlings will be prevented (Wanless *et al.,*1994), thus creating larger tidal creeks. Higher tidal amplitude will expand these creeks and allow for saline waters to penetrate further into the wetlands, thus killing salt intolerant species further inland (Jiang *et al.,* 2011). Where salt water intrusion occurs in peat soils, the wetlands are converted to open creeks, ponds, and basins (Wanless and Vlaswinkel, 2005) that may have SAV but cannot be considered wetlands. In marl wetlands, salt water intrusion results in a zone of lower productivity along the coastal margins of the wetland (Ross *et al.,* 2002).

Collectively, these mechanisms of change will ultimately result in the loss of land along the coasts. In the southern three provinces, coastal wetlands will presumably move inland with concurrent loss of freshwater habitats further from shore (Davis *et al.,* 2005). Shoreline hardening (e.g., seawalls, rip rap, etc.) and associated urban development in the northernmost province will prevent the migration of coastal wetlands inland. However, increased freshwater flow to the coastal wetlands associated with Everglades restoration may prevent or mitigate some of these impacts (Davis *et al.,* 2005; Jiang *et al.,* 2011; Lorenz and Freeza, 2011).

Sediment Supply

The primary sources of sediment to the coastal wetlands are marine deposits that wash ashore during storm surges, peat production by mangroves and coastal marshes, and sediment carried to the coast from inland (Krauss *et al.,* 2003; Odum *et al.,* 1982; Sklar and Browder, 1998). In a study conducted in Micronesia, mangrove forests have been shown to capture and stabilize the sediments, and this process may have implications in mitigating the effects of sea-level rise along the southwest Florida coast (Krauss *et al.,* 2003). A concern is that diverting or limiting freshwater flow affects the sediments carried by the rivers, which affects the supply of raw materials to maintain or build up the coast and nutrients to promote plant growth, factors especially important in allowing the coastal wetlands to keep pace with rising sea levels (Sklar and Browder, 1998).

Mangrove Production and Peat Accretion

Wanless *et al.* (1994) estimated that mangroves can accumulate peat up to 30 cm per century; Davis *et al.* (2005) estimated 20-60 cm per century. However, if the rates of sea-level rise surpass the ability of the mangroves to keep pace, Wanless *et al.* (2000) predicts "catastrophic loss of the coastal mangrove fringe" and inundation and/or erosion of the low-lying coastal wetlands. Undeveloped land allows for natural migration of the mangroves and marshes inland as sea level rises (Scavia *et al.,* 2002). Within the Everglades Province, these changes will probably result in the landward expansion of the red mangroves and a possible loss of species diversity within the forests as the salt-tolerant species invade the upland freshwater ecotones (Jiang *et al.,* 2011). In the Barrier Islands, Ten Thousand Islands, and Cape Sable areas, the ability of the mangroves and marshes to retreat is limited because of island physiography or urban development. In these regions, complete loss of the ecotone is possible. There is some speculation that increased air, soil, and water temperatures could stimulate growth and the expansion of salt marshes and mangrove forests as the southern excursion of low temperature events retreat northward (Scavia *et al.,* 2002).

Coastal Nutrient Dynamics

Mangroves and coastal marsh systems generally act as filters or traps for a number of elements, including nitrogen, phosphorus, trace elements, and heavy metals through combined interaction of the plants themselves, the soils, and the organisms that live there (Odum and McIvor, 1990; Estevez, 1998; Sklar and Browder, 1998). These elements may be stored in the wetlands for many years. This filtration reduces the amount of nutrients and potential pollutants entering the estuaries and marine system via runoff (Estevez, 1998; Sklar and Browder, 1998).

Tidal Channel Dynamics

As stated previously, flushing and flow of water are critical components of the mangrove forests and tidal wetlands. The tidal channels carry marine waters and phosphorus into the forests and wetlands (Davis *et al.,* 2005) and flush organic matter out into the estuaries and marine environment (Odum and McIvor, 1990). The most productive systems occur where the most flushing of fresh and tidal waters occurs (Twilley *et al.,* 1986). The extent of the tidal reach also affects the distribution of the plant species and the community structure (Odum and McIvor, 1990; Jiang *et al.,* 2011). Many tidal channels were lost to sediment infilling in the 20th century, partly in response to rising sea level and changes in freshwater delivery to the coast (Davis *et al.,* 2005). Restoration of more natural flow rates may reopen these channels, but rising sea level will affect the patterns of connectivity throughout the coastal wetlands (Davis *et al.,* 2005).

Research Directions

Remote sensing techniques will play a big role in monitoring and assessing the response of the coastal wetlands to sea-level rise, climate change, storms, invasive species, alterations of freshwater flow, and other factors (Kuenzer *et al.,* 2011). By using ground-truthing and training datasets, Landsat images can be used to determine changes in the spatial extent of mangroves (Alatorre *et al.,* 2011) and to monitor shoreline erosion (Yu *et al.,* 2011). Responses of vegetation to changes in quantity and quality of available water and recovery from storms can be measured through spectral analyses (Lagomasino *et al.,* 2011; Wang, 2012). In addition to mapping mangrove type and distribution, synthetic aperture radar has also been used to determine mangrove health and to estimate the above-ground biomass and carbon storage capacity for mangrove ecosystems (Fatoyinbo *et al.,* 2011). Elevation data from the Shuttle Radar Topography Mission, in combination with airborne light detection and ranging (LIDAR) technology, has been used to estimate mean tree height and to produce a map of the standing biomass of the mangrove forests along the southwest coast of Florida (Simard *et al.,* 2006). LIDAR has also been used to detect small-scale changes, such as gaps caused by storms, frost events, lightning, or other factors that may have an impact on forest regeneration (Zhang, 2008).

To provide a longer time series, future satellite imagery and remote sensing techniques can be digitally compared to georectified historic maps and aerial photos (images and data available at http://sofia.usgs.gov/publications/ofr/02-204/html/mosaic.html). Comparison of recent aerial photographs to historical charts has indicated a retreat of the shoreline near the mouth of Shark River Slough of 250-500 m between 1889 and 2004 and has highlighted different patterns of change in the northern and southern sections of the southwest Florida coastline (Smith *et al.,* 2010). In addition, shifts in habitat at Cape Sable have been documented (Smith *et al.,* 2010). These historic databases serve as a baseline of comparison for future researchers using remote sensing techniques.

Carbon and nutrient cycling in the coastal wetlands are also receiving a lot of attention in recent studies, in part because they serve as both a carbon sink and a producer of methane gas. An investigation by Mitsch *et al.* (2013) indicates that "almost all wetlands are net radiative sinks when balancing carbon sequestration and methane emissions." Information on factors that regulate the distribution and productivity of the mangroves and coastal marshes is needed, for example, hydroperiods, soil composition, accretion and elevation, and nitrogen cycling (Rivera-Monroy *et al.,* 2011). Stable isotopic studies can be used to determine the sources of organic matter in the coastal wetlands and to trace the movement of materials through food webs (Rivera-Monroy *et al.,*2011).

These techniques, along with emerging technology, will allow for relatively rapid and easy assessment of changes or loss of wetland habitats along the southwest coast of Florida. By monitoring these changes, management decisions that impact these wetlands can be more informed and adaptable to protecting these ecologically and socially important coastal habitats.

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