

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

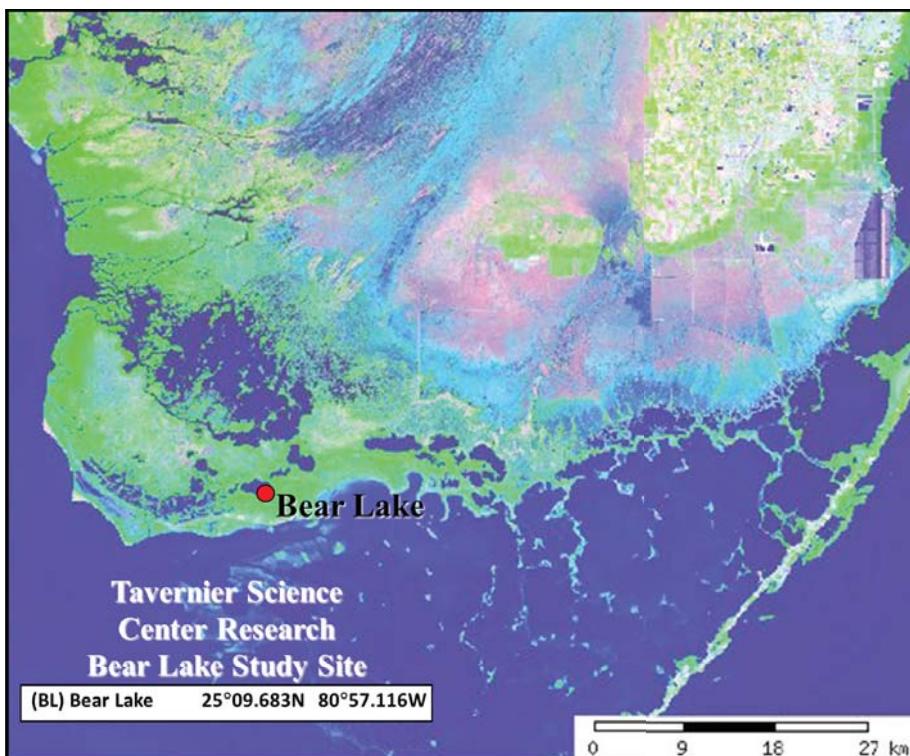


Figure 1. Map of the Southwest Florida Shelf subregion provinces. Note the Bear Lake study site in Cape Sable Province.

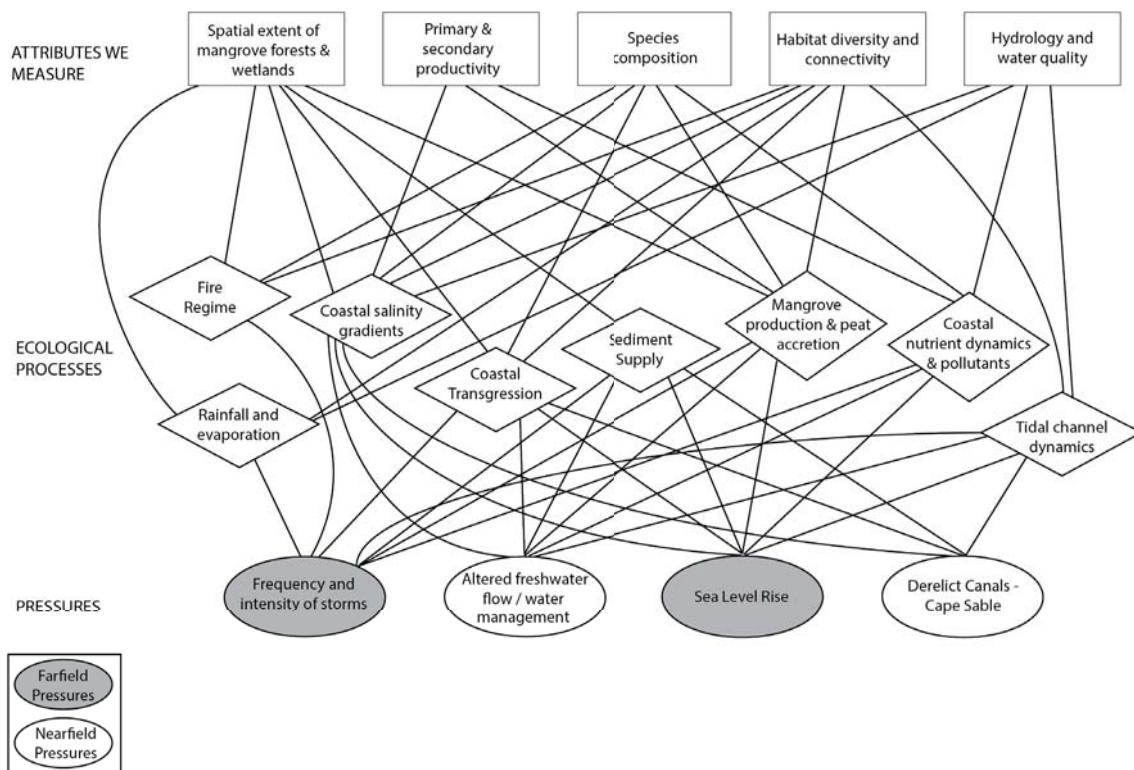


Figure 2. Coastal wetlands submodel diagram for the Southwest Florida Shelf.

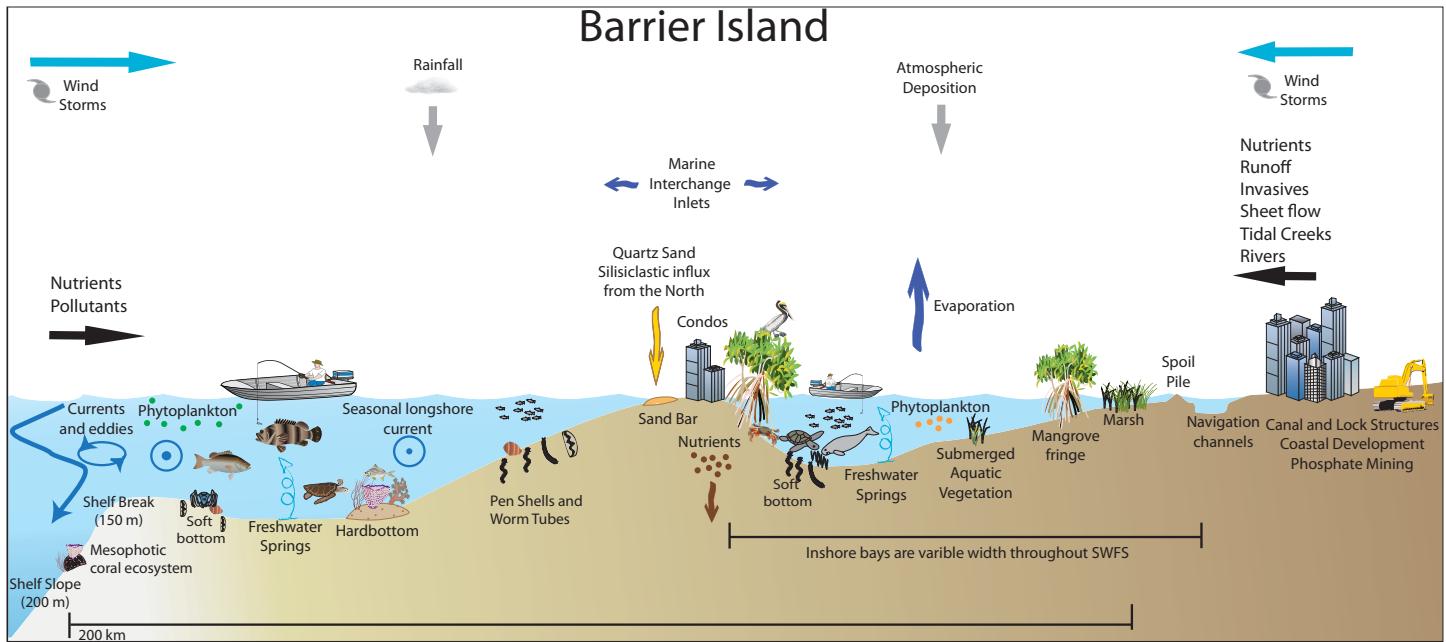


Figure 3a. Conceptual diagram of the Southwest Florida Shelf Barrier Islands Province ecosystem, processes operating upon it, and factors affecting its condition.

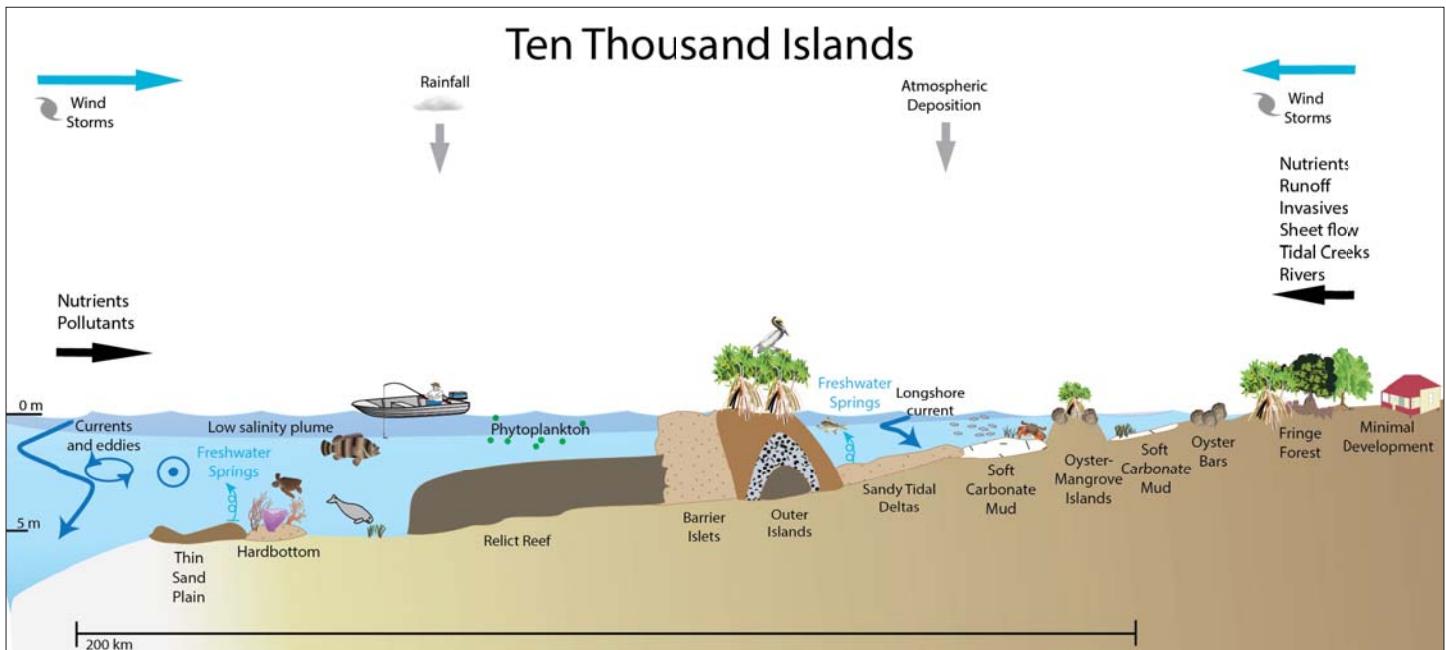


Figure 3b. Conceptual diagram of the Southwest Florida Shelf Ten Thousand Islands Province ecosystem, processes operating upon it, and factors affecting its condition.

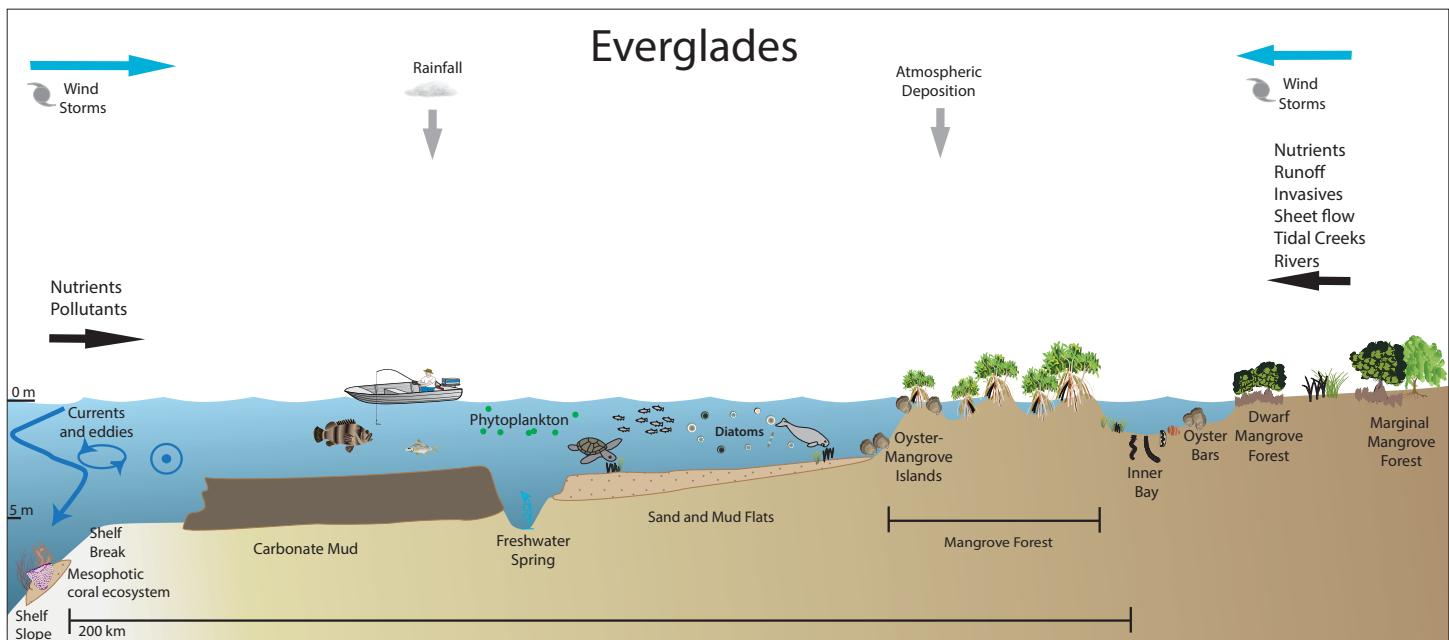


Figure 3c. Conceptual diagram of the Southwest Florida Shelf Everglades Province ecosystem, processes operating upon it, and factors affecting its condition.

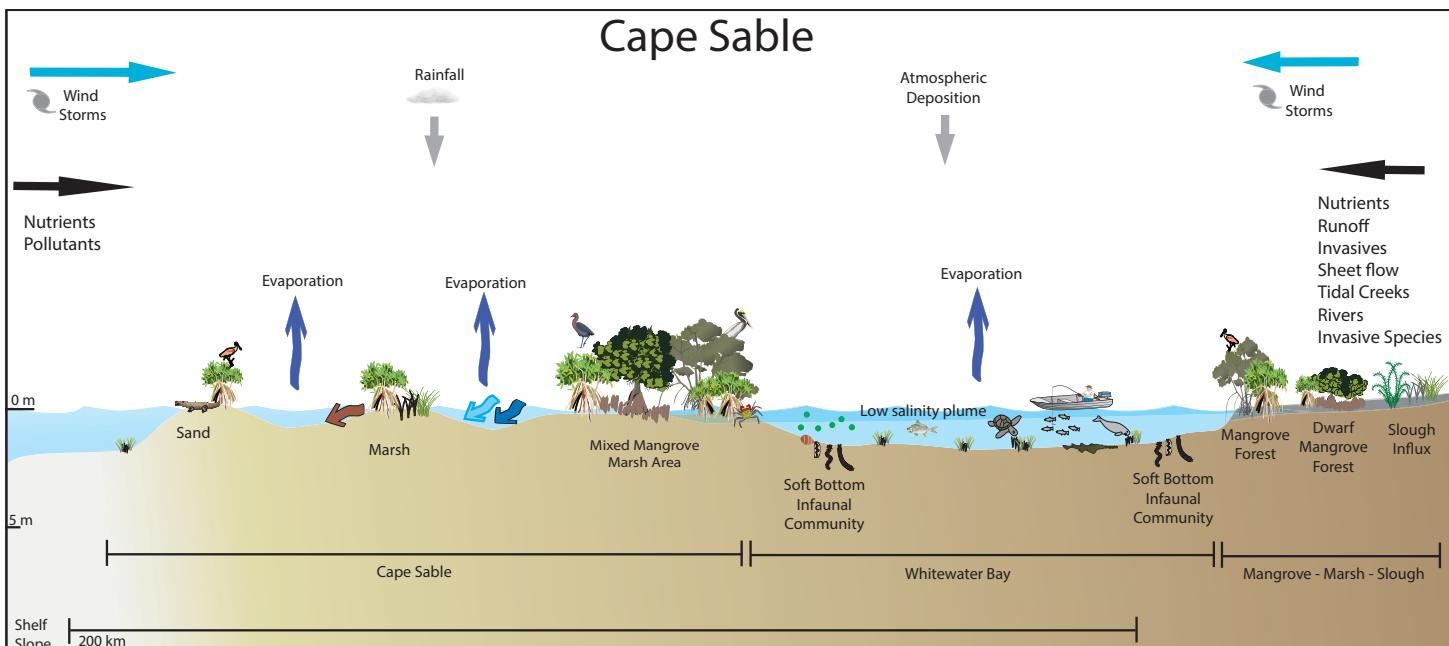


Figure 3d. Conceptual diagram of the Southwest Florida Shelf Cape Sable Province ecosystem, processes operating upon it, and factors affecting its condition.

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 racemosa*) (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 pneumatophores). 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 Wiegert, 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 $\text{CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$) than northern peatlands (averaging 20-30 g $\text{CO}_2 \text{ m}^{-2} \text{ yr}^{-1}$) 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/m²/day for a red mangrove forest to 7.5 gC/m²/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	<i>Crocodylus acutus</i>	Threatened
Bald eagle	<i>Haliaeetus leucocephalus</i>	Delisted Monitored
Garber's spurge	<i>Chamaesyce garberi</i>	Threatened
Green sea turtle	<i>Chelonia mydas</i>	Endangered
Hawksbill sea turtle	<i>Eretmochelys imbricata</i>	Endangered
Kemp's Ridley sea turtle	<i>Lepidochelys kempii</i>	Endangered
Leatherback sea turtle	<i>Dermochelys coriacea</i>	Endangered
Loggerhead sea turtle	<i>Caretta caretta</i>	Threatened
Piping plover	<i>Charadrius melanotos</i>	Threatened
Roseate tern	<i>Sterna dougallii dougallii</i>	Threatened
Smalltooth sawfish	<i>Pristis pectinata</i>	Endangered
West Indian manatee	<i>Trichechus manatus</i>	Endangered
Wood stork	<i>Mycteria americana</i>	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 (Marmor, 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

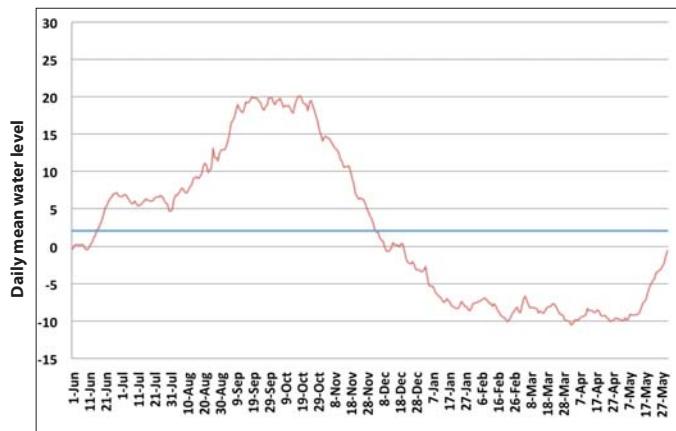


Figure 4. Annual water level cycle at Bear Lake (Figure 1) on Cape Sable for an averaged hydrologic year (June–May). Data are in centimeters and are relative to the ground level of the surrounding ephemeral wetlands such that zero represents the water depth at which these peripheral seasonal wetlands 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).

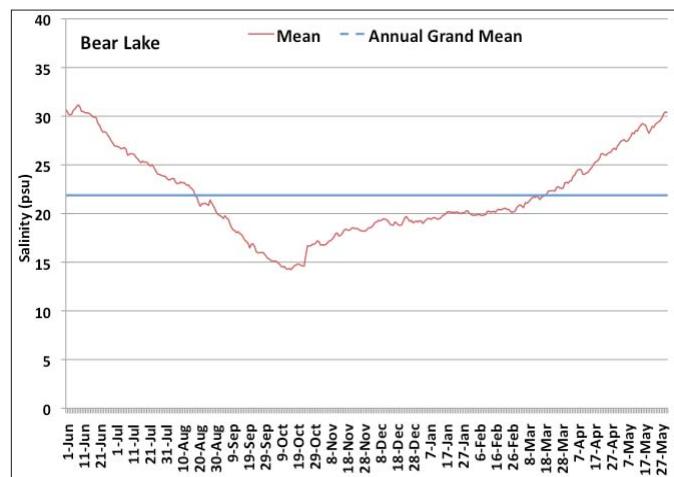


Figure 5. Annual salinity cycle at Bear Lake on Cape Sable for an averaged hydrologic year (June–May). The daily mean water level was calculated from a 10-year period of record (2000–2010). The horizontal line represents overall mean water level for the period of record. Adapted from Robinson *et al.*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