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Integrated conceptual ecological model and habitat indices for the southwest Florida coastal wetlands

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ABSTRACT

The coastal wetlands of southwest Florida that extend from Charlotte Harbor south to Cape Sable, contain more than 60,000 ha of mangroves and 22,177 ha of salt marsh. These coastal wetlands form a transition zone between the freshwater and marine environments of the South Florida Coastal Marine Ecosystem (SFCME). The coastal wetlands provide diverse ecosystem services that are valued by society and thus are important to the economy of the state. Species from throughout the region spend part of their life cycle in the coastal wetlands, including many marine and coastal-dependent species, making this zone critical to the ecosystem health of the Everglades and the SFCME. However, the coastal wetlands are increasingly vulnerable due to rising sea level, changes in storm intensity and frequency, land use, and water management practices. They are at the boundary of the region covered by the Comprehensive Everglades Restoration Plan (CERP), and thus are impacted by both CERP and marine resource management decisions. An integrated conceptual ecological model (ICEM) for the southwest coastal wetlands of Florida was developed that illustrates the linkages between drivers, pressures, ecological process, and ecosystem services. Five ecological indicators are presented: (1) mangrove community structure and spatial extent; (2) waterbirds; (3) prey-base fish and macroinvertebrates; (4) crocodilians; and (5) periphyton. Most of these indicators are already used in other areas of south Florida and the SFCME, and therefore will allow metrics from the coastal wetlands to be used in system-wide assessments that incorporate the entire Greater Everglades Ecosystem.

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1. Introduction

Coastal wetlands form a critical ecotone at the boundary between freshwater and marine environments and thus provide essential habitats and nutrients to both systems. They are valued by society because they stabilize the coastline and provide protection from storm surge and flooding, improve water quality by filtering nutrients, sequester carbon, and provide aesthetic, recreational and tourism value. Yet, 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. In south Florida, availability of freshwater also is affected by water-management practices, and restoring flow of freshwater through the wetlands is a key component of the Comprehensive Everglades Restoration Plan (CERP; see Ortner et al., 2014). The goal of this paper is to provide an Integrated Conceptual Ecological Model (ICEM) for the southwest Florida coastal wetlands and to highlight indicators that can be used to monitor natural and anthropogenic change in the coming decades. A tremendous amount of research has been conducted on this region of Florida and it is not within the scope of this paper to provide a thorough review. The references included support the development of the ICEM and selection of the indicators.

1.1. Area included in the model

Within the context of the MARES (MARine and Estuarine goal Setting; see Ortner et al., 2014) Southwest Shelf 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 (Fig. 1). The entire region is characterized by gently sloping topography with elevations less than a few meters above sea

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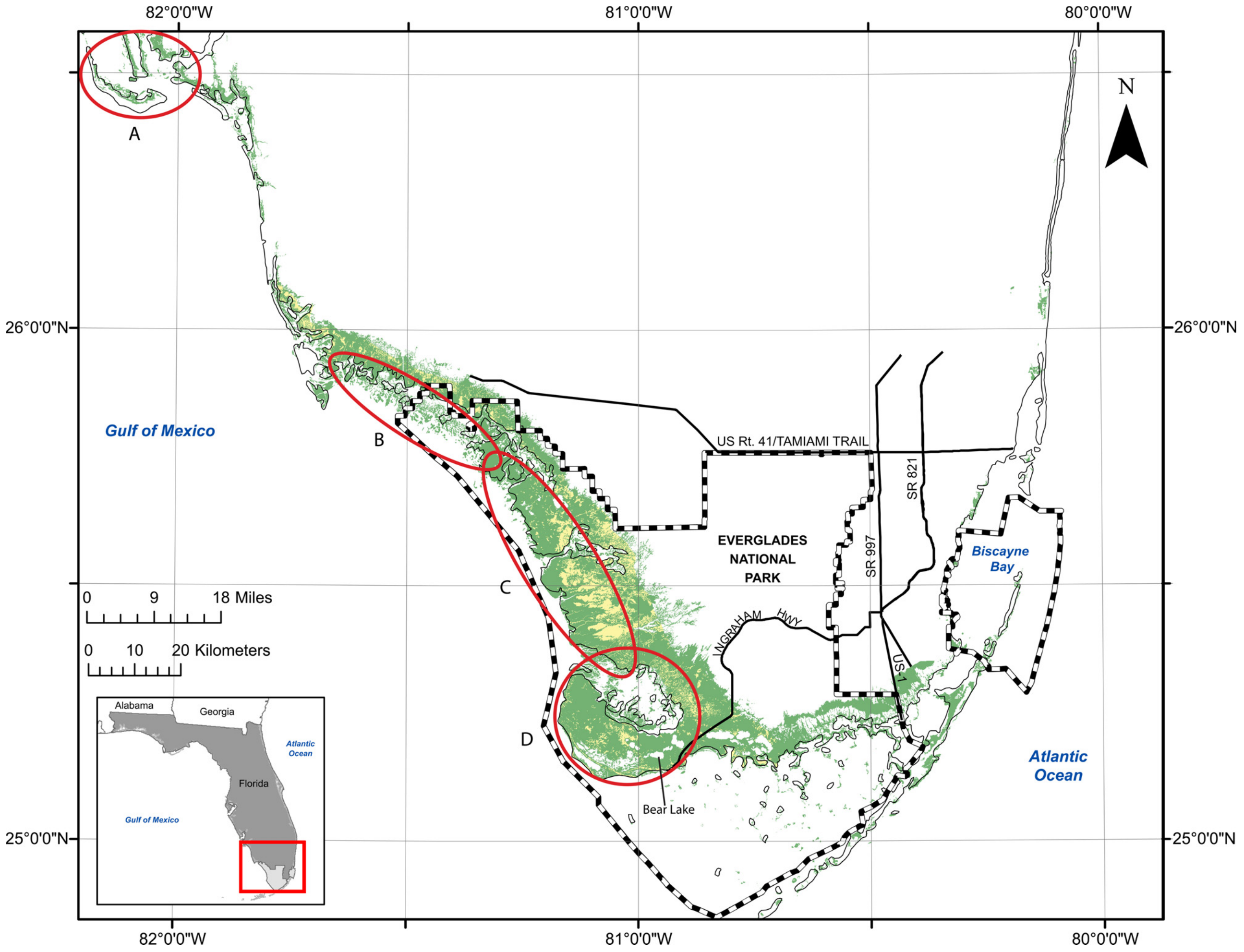

Fig. 1. Map of southern Florida showing the distribution of the southwest coastal wetlands. Mangroves are shown in green and salt marsh areas in yellow (salt marsh only shown for areas inside Everglades National Park). The position of Everglades National Park, and the four provinces discussed in the text (red ovals) are shown: (A) barrier island province, (B) Ten Thousand Island province, (C) Everglades/Shark River Slough province, and (D) Cape Sable/Whitewater Bay province. (For interpretation of the references to color in text, the reader is referred to the web version of this article.)

Mangrove distribution data from Florida Fish and Wildlife Conservation Commission (2011).

level (Zhang, 2011). The southwest Florida coastal zone includes more than 60,000 hectares of mangroves (Smith et al., 1994), 161,996 hectares of estuarine forested scrub–shrub (includes mangrove forests, dwarf mangroves, and buttonwoods), and 22,177 hectares 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. The southwest Florida coastal wetlands are divided into four provinces (Fig. 1) based on the dominant coastal features: Barrier Island, 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 (Fig. 2). There are, however, differences in some ecosystem services and the role of the drivers for each of the four provinces. These differences were compiled into cross-sectional transect figures for each region (see Fletcher (2014) for an example; see Nuttle and Fletcher, 2013 for four diagrams of southwest Florida provinces).

The barrier islands are the most unique of the four provinces because they are extensively developed compared 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 south (see Marshall et al. (2014) for discussion of issues related specifically to beaches). The urbanization of the barrier islands 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 ground water to provide drinking water (Barnes, 2005). Besides direct urbanization in the barrier island province, the overall development of southern Florida has led to large scale changes in water management practices (defined here as the anthropogenic storage and distribution of water) resulting in polluted water from Lake Okeechobee being discharged in much larger quantities than natural into the inshore bays through the Caloosahatchee River (Barnes, 2005; Light and Dineen, 1994; Lodge, 2010). This discharge of polluted water 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." 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 then the Ten Thousand Islands,

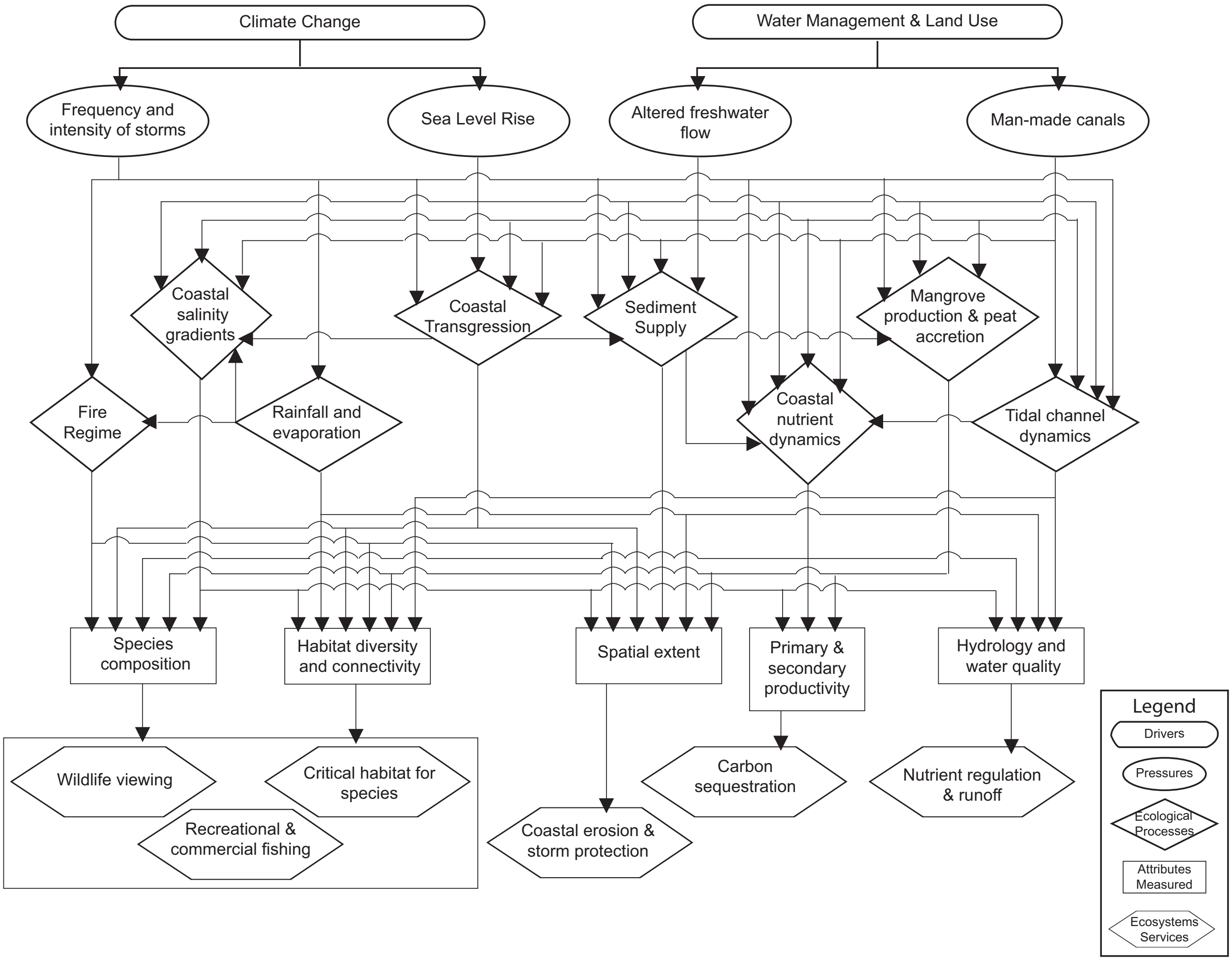

Fig. 2. Integrated conceptual ecological model diagram for the southwest Florida coastal wetlands. This diagram shows the connections between components of the ecosystem discussed in the text and is not intended to include all aspects.

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 to 30 km inland (Zhang et al., 2012). Dwarf mangrove forests are also a major component of the landscape in 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 (Schomer 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., 2012), and it is separated from the Everglades province by Whitewater Bay (Schomer and Drew, 1982).

1.2. Role of the coastal wetlands in the greater Everglades and the south Florida coastal marine ecosystems

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 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; (5) aesthetic, educational, sport and tourist value (Field et al., 1991; Odum et al., 1982); and (6) carbon sequestration (Chmura et al., 2003; Mitsch et al., 2012).

Biodiversity of the southwest Florida coastal wetlands is significant because species from terrestrial, freshwater, estuarine and marine environments utilize the wetlands 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 utilize the mangroves of southern Florida. The mangroves form the essential framework of this habitat. There are three species of mangroves in southwestern Florida: red (*Rhizophora mangle*), black (*Avicennia germinans*) and white (*Laguncularia racemosa*) mangroves (Lugo and Snedaker, 1974). Buttonwood (*Conocarpus erectus*), a mangrove associate, is also common in mangrove forests in southern Florida. Tidal forces, climatic conditions and soil type result in these species forming six different forest types: overwash, fringe, riverine, basin, hammock and scrub forests (Lugo and Snedaker, 1974). The arrangement of the species within forest type determines the biota that 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; Granek et al., 2009; Odum and Heald, 1975).

As indicated by the number of species present, these coastal wetlands are highly productive. Small demersal fishes 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. The 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 (Cannicci et al., 2008; Surge et al., 2003); the mangroves therefore play a role in seagrass and oyster reef ecosystems. Movements of large predators such as Bull sharks (*Carcharhinus leucas*) and American alligators (*Alligator mississippiensis*) may also result in the transport of nutrients in the form of consumed prey from these wetlands into the freshwater habitats of the Everglades, thereby influencing upstream freshwater marsh habitats (Matich et al., 2011; Rosenblatt and Heithaus, 2011). Furthermore, organic export from mangrove forests provides nutrients to surrounding ecosystems (Lugo and Snedaker, 1974; Nixon, 1980; Odum and Heald, 1975; Twilley, 1985, 1988) but mangrove forests and coastal wetlands, depending on type and location, also can sequester nutrients and act as a waste water filter (Ewel et al., 1998) thereby playing a role in water quality as well.

2. Ecosystems services provided by the coastal wetlands

The features of the mangroves and wetlands of the southwest Florida coast described in Section 1.2 contribute to the critical ecosystems services provided to the entire southwest coastal ecosystem. These ecosystems services include the following attributes.

2.1. 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., 2012). 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 increases. For salt marshes, they found a four-fold decrease in wave height with increasing distance inland (Barbier et al., 2008).

Zhang et al. (2012) 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., 2012). 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% further inland, causing significant damage to the areas inland from the mangroves (Zhang et al., 2012).

2.2. Critical habitat for protected species and for 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 US 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 Endangered and Threatened Species 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 (*Epinephelus itajara*)), marine mammals (e.g. bottlenose dolphin (*Tursiops truncatus*)), 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 100–250 thousand nesting pairs of wading birds, but today these colonies only support several hundred to several thousand pairs (Ogden, 1994).

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

Common name	Scientific name	Status
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

2.3. 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 Florida 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 Florida coastal marshes. In addition, numerous species of birds use the wetlands as wintering or stopover sites during their annual migration (Odum et al., 1982).

2.4. Recreational and commercial fishing

Coastal wetlands provide critical habitat in the life cycle of many important commercial and recreational fishes as both shelter and 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 (*Crassostrea virginica*), blue crabs (*Callinectes* *sapidus*), Caribbean spiny lobsters (*Panulirus argus*), pink shrimp (*Farfantepenaeus duorarum*), common snook (*Centropomus undecimalis*), mullet (*Mugil* spp.), menhaden (*Brevortia* spp.), red drum (*Sciaenops ocellatus*), spotted sea trout (*Cynoscion nebulosus*), snapper (*Lutjanus* spp.), tarpon (*Magalops atlanticus*), ladyfish (*Elops saurus*), jacks (*Caranx* spp.), and others (Odum et al., 1982). Salt marshes also serve as important nursery and feeding grounds for estuarine animals (Montague and Wiegert, 1990).

2.5. *Carbon sequestration*

Coastal wetlands provide globally important carbon reservoirs, and the most carbon sequestration occurs in tropical and subtropical wetlands (Mitsch et al., 2012). Twilley et al. (1986) estimate that the litter fall in fringing mangrove swamps of south Florida ranges between 1.86 and 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). An investigation by Mitsch et al. (2012) indicates that “almost all wetlands are net radiative sinks when balancing carbon sequestration and methane emissions.” 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.

2.6. *Nutrient regulation and filtration for wastewater and storm-water 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 (Estevez, 1998; Odum and McIvor, 1990; 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).

3. Drivers of change in the coastal wetlands and resulting pressures

The ecosystems services described in Section 2 are not static but are subjected to the forces that affect the ecosystem. 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 and land use 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 loss of coastal wetlands (Krauss et al., 2011; Wanless et al., 1994). In the Barrier Island province development will prevent inland migration and in the Ten Thousand Island 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 also will 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). Following is a description of the specific pressures that impact the southwest Florida coastal wetlands as a result of the larger-scale drivers.

3.1. *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% 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 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 (*C. virginica*) and, therefore, the entire oyster reef ecosystem (Volety et al., 2009). Even if flow is not altered significantly to affect oysters directly, less damaging changes in salinity have been shown to alter the oyster reef community of fish and crustaceans (Tolley et al., 2006).

Productivity of the coastal wetlands is affected by the balance between nutrients that enter the system through freshwater runoff and through the influx of marine water. A defining characteristic of the Everglades is the “upside-down” oligotrophic nature of the system, with the upstream region limited in phosphorous (Childers et al., 2006; Rivera-Monroy et al., 2011). This means that the primary source for phosphorous to the coastal wetlands is the marine system. Childers et al. (2006) found a strong positive relationship between increases in salinity and increases in total phosphorous in Shark River Slough. During the wet season, the phosphorous gradient is compressed toward the mouth of the river system, whereas during the dry season it migrates upstream (Childers et al., 2006). This relationship between hydrology and nutrients means that water management practices can have a significant effect on water quality and biogeochemical cycles in the coastal wetlands. 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). In addition, altered hydroperiods and flow regimes can lead to the invasion of opportunistic native plants and invasive exotics (Sklar and Browder, 1998).

3.2. *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 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 (Jiang et al., 2011; Krauss et al., 2011; Wanless et al., 2000). Davis et al. (2005) indicate that sea level rise will likely be the most significant challenge to sustainability of the coastal mangroves.

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 to 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 m" by 2100, with an upper limit at approximately two meters.

3.3. *Frequency and intensity of storms*

A number of factors determine the effects that a hurricane will have on the coastal wetlands, including the path of the storm, wind speed, velocity, and duration (Castañeda-Moya et al., 2010; Zhang, 2008). The effects of hurricanes and their associated storm surges on the mangroves and marshes have been studied following hurricanes Andrew in 1992, Charlie in 2004, 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). In the Barrier Island province, damage to mangroves from Hurricane Charlie was exacerbated by anthropogenically restricted flows and recovery was prolonged as well (Harris et al., 2010).

Conversely, storms can play a positive role in long-term sustainability of the coastal wetlands. Castañeda-Moya et al. (2010) discuss the increase in vertical accretion of sediments and in total phosphorous concentrations following the onshore storm surge associated with hurricane Wilma. They propose that this feedback mechanism between hurricane disturbance and sediment and nutrient influx may explain how salt marshes and mangroves adapt to sea-level rise (Castañeda-Moya et al., 2010) and therefore, are potentially an important component of coastal wetland sustainability in the future. Twilley (2007) also discusses the positive role of hurricanes to the coastal wetlands from a combination of increased runoff providing additional water and nutrients and onshore deposition from storm surges. Twilley concludes that the net effects of storms are dependent on specific local conditions, but may be more negative than positive.

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 number and intensity of tropical storms in the North Atlantic (Mann et al., 2009) and an increase of one degree C in global sea surface temperatures resulted in a 30% increase in category 4 and 5 storms worldwide (Elsner et al., 2008). The Copenhagen Diagnosis (Allison et al., 2009) discussed 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 (Aumann et al., 2008; Trap et al., 2007). In addition to wind and rainfall, thunderstorms play a role in fire generation in south Florida (Gunderson and Snyder, 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.

3.4. *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, promoting subsidence and saltwater intrusion (Sklar and Browder, 1998), exacerbating the impact of hurricanes and prolonging post storm recovery (Harris et al., 2010). 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 also is 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 (Wanless and Vlaswinkel, 2005; 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 to 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 (30.5 m) thick steel and earthen structures; however, a third canal at the north end of Lake Ingraham failed in November of 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.

4. Mechanisms of change – description of Ecological Processes

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

4.1. 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 and May) when the region is still dry and the lightning storms are just beginning. Wade et al. (1980) has correlated increased development with altered pattern and frequency of fires in nearby undeveloped areas. For the coastal wetlands, the human development factor is particularly important in the barrier island province, somewhat in the Ten Thousand Islands province, 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 Old World climbing fern (*Lygodium microphyllum*), 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).

4.2. 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; Schomer 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 increased likelihood of hurricanes and changes in atmospheric temperature is unclear (Scavia et al., 2002). Predicted increases in global temperatures (Allison et al., 2009; IPCC, 2007) will lead to increased evaporation rates. Less rainfall and increased evaporation rates, combined with rising sea level discussed above, suggests there may be less freshwater available to the southwest Florida coastal wetlands in the future.

4.3. 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 and location of the ecotones (Krauss et al., 2011).

Freshwater flow through the Everglades to the SFCME has been greatly altered by modern water management practices (Light and Dineen, 1994). The Comprehensive Everglades Restoration Plan is an effort to return Everglades freshwater flows to a more historic condition thereby restoring natural flows to the SFCME (Ogden et al., 2005b), It is believed that these effort will reduce detrimental flows to the Caloosahatchee Estuary (Barrier Islands Province) and increase freshwater flow to the other three provinces (Ogden et al., 2005b). If successful, these restoration efforts will have profound implications for coastal salinity gradients throughout the SFCME. How these efforts manifest themselves is complex and beyond the scope of this manuscript, however, Davis and Ogden (1994) present a vision of how restoration efforts may affect the existing landscape.

4.4. 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, 2000). Wanless et al. (1994) indicate that wetland soil accretion is unlikely to keep up 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 submerged aquatic vegetation but cannot be considered wetlands In marl wetlands, salt water intrusion may result 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 northern most 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).

4.5. 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); however, in situ plant productivity is considered the dominant factor in soil production (Twilley, 2007). Castañeda-Moya et al. (2010) demonstrated the role of storm surge deposition, documenting a vertical sediment accretion in the mangroves ranging from 0.5 to 4.5 cm following hurricane Wilma. These values are 8 to 17 times greater than the annual sediment accretion rate (Castañeda-Moya et al., 2010). 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 up with rising sea level (Sklar and Browder, 1998).

4.6. 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 zones (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 habitat 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).

4.7. 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 (Estevez, 1998; Odum and McIvor, 1990; Sklar and Browder, 1998). These elements may be stored in the wetlands for many years, which reduces the amount of nutrients and potential pollutants entering the estuaries and marine system via runoff (Estevez, 1998; Sklar and Browder, 1998). Storm deposition of phosphorous from the marine system into the coastal wetlands is especially important because the southwest coastal system is phosphorous limited (Castañeda-Moya et al., 2010). Following hurricane Wilma, Castañeda-Moya et al. (2010) found total phosphorous in the storm deposits was two times the surface soil density and they suggest that the elevated phosphorous explains the high mangrove biomass near the mouth of Shark River.

4.8. 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 (Jiang et al., 2011; Odum and McIvor, 1990). 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).

5. Attributes scientists measure

In order to assess the status and trends of the coastal wetlands scientists monitor and analyze the following attributes of the system.

5.1. Spatial extent

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 Keys due to land development (Spalding et al., 1997). In fact, Krauss et al. (2011) have documented a 35% 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). In contrast, 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 georectified historic maps and aerial photos (images and data available at http://sofia.usgs.gov/publications/ofr/02-204/html/mosaic.html) can serve as a baseline of comparison for future researchers using satellite imagery and remote sensing.

Remote sensing techniques, linked to strategic ground-surveying and geographic information systems (GIS) analyses, provide valuable assessment and management tools for understanding changes to the spatial extent of the coastal wetlands. The response of the coastal wetlands to sea level rise, climate change, storms, invasive species, alterations of freshwater flow, and other factors can be monitored through remote sensing (Kuenzer et al., 2011). These techniques provide a means for retrieving the metric data for the mangrove community structure and spatial extent indicator. 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). LIDAR also has 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).

5.2. 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, and 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) and phosphorous from the marine environment (Childers et al., 2006; Rivera-Monroy et al., 2011). 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).

5.3. *Primary and secondary productivity*

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 Florida 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).

Rivera-Monroy et al. (2011) discuss the significant information gaps that exist in understanding the productivity of the coastal wetlands. Historically, measurements of primary productivity have been made using gas exchange, litter fall, changes in tree diameter, or other methods (Odum et al., 1982; Twilley et al., 1986), and can provide a means of assessing the health of the coastal wetlands and determining ecological responses to changing conditions. Biomass is one measure of organic production in the mangrove ecosystem, and it can be a useful tool for comparing systems (Carter et al., 1973; Lugo and Snedaker, 1974; Odum et al., 1982; however many variables affect biomass and productivity including interactions and cumulative effects of gradients in salinity, sulfides, and nutrients; hydroperiods; and a number of other factors (Rivera-Monroy et al., 2011). Also, different species of mangroves partition biomass very differently, and their responses are affected by age of the forest, stand history (e.g. hurricane impacts), structural differences, tidal transport, nutrients, etc. (Lugo and Snedaker, 1974; Odum et al., 1982). In addition, estimates of biomass in mangroves often exclude the root structures (Odum and McIvor, 1990); however, soil accretion rates and subsidence can readily be measured (Lovelock et al., 2011; McKee, 2011; McKee et al., 2007). These authors demonstrated that myriad factors influence accretion rates (e.g. soil type, leaf litter, algal turf production water depth) and that subsidence rates can effectively cancel out accretion rates. A net increase in soil accretion will be needed to maintain mangrove forests in the face of sea level rise (Lovelock et al., 2011; McKee, 2011; McKee et al., 2007) and measuring accretion and subsidence rates provides a powerful tool for determining the future health of these ecosystems.

Several remote sensing techniques can be used to estimate biomass. Synthetic Aperture Radar (SAR) has been used to assess 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 (SRTM), 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 mangroves (Simard et al., 2006).

The mangrove forests are linked to the southwest coastal ICEM because they provide a critical component of estuarine productivity in the southwest Florida 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).

5.4. *Species composition (including exotics)*

The coastal wetlands contain a mixture of mangrove species along with varying occurrences of emergent and submerged aquatic vegetation (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 (*Farfantepenaeus duorarum*) (Kaplan, 1988; Odum et al., 1982). 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 (Ogden et al., 2014). 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 vertebrate species listed by the US Fish and Wildlife Service as endangered or threatened utilize 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

Table 2
Median, minimum and maximum for the most common water quality parameters for the coastal wetlands.

Variable	Median	Min.	Max.	*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

Source: J. Boyer, Plymouth State University, NH.

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 (Fourqurean et al., 2009; Gunderson, 1994; 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 (Stackhouse et al., 2012a,b). 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 utilize 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.

5.5. *Hydrology and water quality*

Coastal wetlands are influenced strongly by the quantity and quality of water available – both surface water and groundwater. 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 Fig. 3 (Robinson et al., 2011). These water level data and the salinity data (see discussion below; Table 2) were collected using a Hach brand sensor and a Campbell brand recorder by 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 also are seasonal, with 60% of the rainfall occurring in from June to September and only 25% 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 (Fig. 4; 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 Fig. 4 were collected at a hydrostation in the interior wetlands of Cape Sable; a region that is largely isolated from direct influence of diurnal tides or water management influences. Although Fig. 4 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). Groundwater plays an important role in any ecosystem, but the coastal wetlands of southwest Florida are developed on porous Pliocene and Pleistocene limestone, which increases the connectivity of the surface and ground waters. Price et al. (2006) describe the important role of coastal groundwater discharge in providing phosphorous to the oligotrophic wetlands. In the southwest coastal region, saline waters intrude inland 6–25 km and can force the discharge of brackish groundwater into the coastal wetlands (Price et al., 2006). Surface water chemistry is strongly linked to seasonality, remaining fresh during the wet season and increasing in salt and calcium concentrations during the dry season (Price et al., 2006).

Typically measured water quality parameters include monthly measurement of salinity, temperature, dissolved oxygen, pH, total phosphorous (TP), total nitrogen (TN), total organic carbon, nitrate, nitrite, ammonium, soluble reactive phosphorus, and chlorophyll *a* (Boyer, 2006). Water samples are generally collected by ship board grab samples (in bottles) along a defined transect; however, there are some water quality platforms that collect bottled samples at predefined intervals and then the samples are analyzed for a sub-set of water quality parameters when the platforms are serviced. The ship board 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

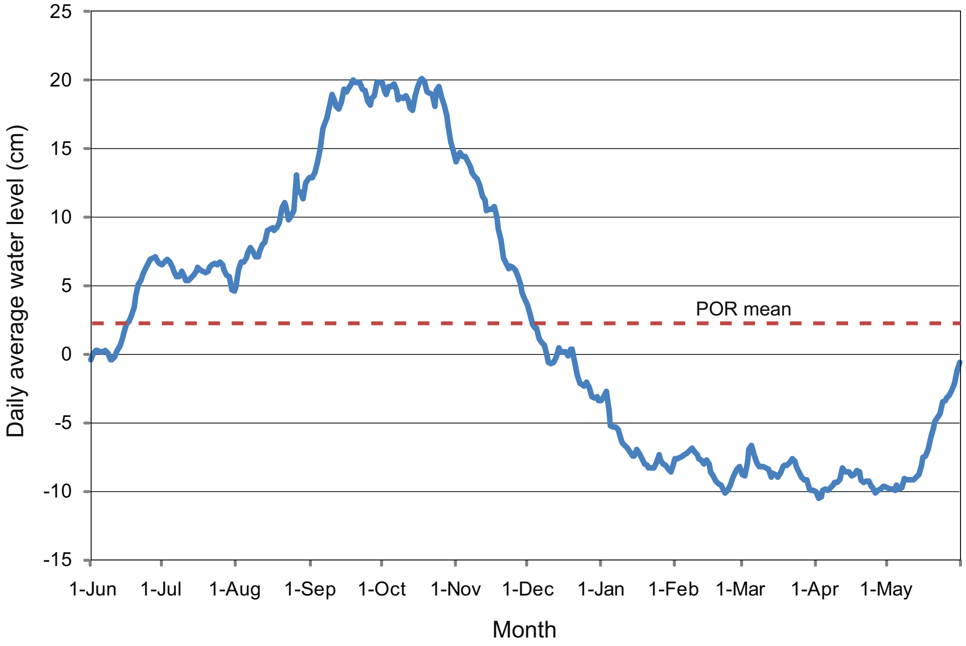

Fig. 3. Annual water level cycle at Bear Lake (see Fig. 1 for location) on Cape Sable for an averaged hydrologic year (June–May). Data are in cm and are relative to the ground level of the surrounding ephemeral wetlands such that zero represents the water depth at which these peripheral seasonal wetlands become dry. The daily mean water level was calculated from a 20-year period of record (1990–2010). The dashed line represents overall mean water level for the period of record (POR).

Adapted from Robinson et al. (2011).

data were collected. Through 2008, ship board samples were collected systematically throughout all four provinces (Boyer, 2006). These data indicate that total phosphorus ranges from 0.005 to 4.02 μM and total nitrogen from 1.5 to 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 underlying differences in water quality in these regions of southwest Florida (Boyer, 2006). Consistent with the "upside-down" estuary described above (Childers et al., 2006; Rivera-Monroy et al., 2011), a strong gradient in estuaries from high N – low P in the south to low N – high P in the north was ascribed to marked differences in land use, freshwater input, geomorphology, and sedimentary geology along this tract

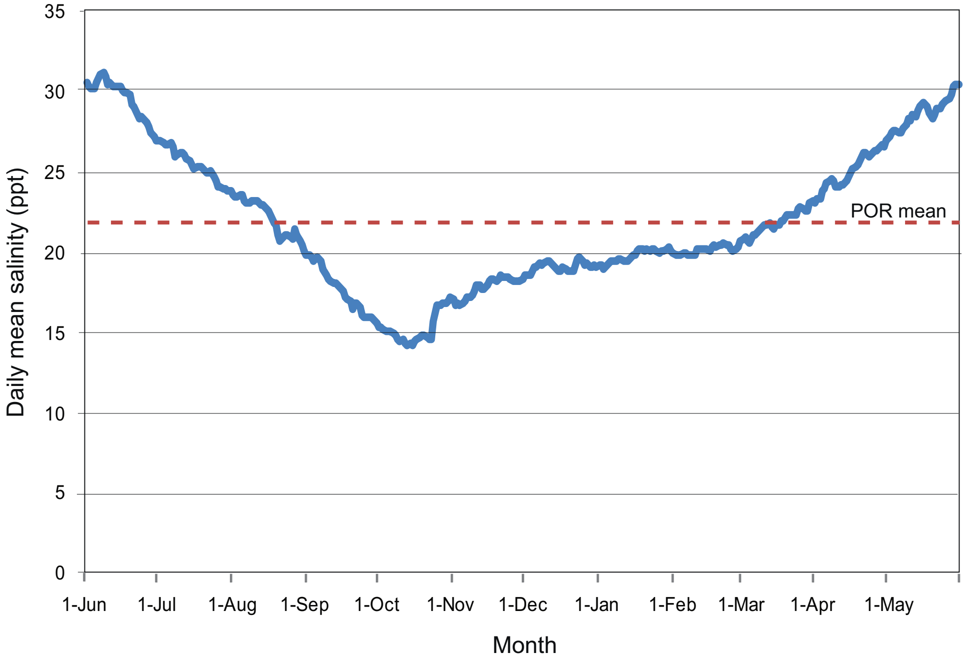

Fig. 4. Annual salinity cycle at Bear Lake (see Fig. 1 for location) on Cape Sable for an averaged hydrologic year (June–May). The daily mean salinity was calculated from a 10-year period of record (2000–2010). The dashed line represents overall mean salinity for the period of record (POR).

Adapted from Robinson et al. (2011).

(Boyer, 2006). These nutrient gradients are believed to be the result of changes in coastal geomorphology and watershed characteristics across the region (Boyer, 2006).

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 P from the water column (Bosence, 1989). Therefore, the more northern estuaries would be expected to be less P-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 (Barnes, 2005; Boyer, 2006; Davis et al., 2005). Freshwater entering the coastal wetlands from the Everglades is very low in nutrients (Noe and Childers, 2007), and much of the nutrient load in the coastal system is provided by the marine environment through diurnal and wind driven tides (Childers et al., 2006; Davis et al., 2005). 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 phosphorous rich water from the Peace River to Charlotte Harbor, which is correlated with algal blooms, red tide, and blackwater events that had profound effects on higher trophic levels on the southwest Florida Shelf (Heil et al., 2007).

Pesticide, herbicide, and pharmacological residues as well as petroleum-based compounds have been measured in these coastal wetlands (Carriger and Rand, 2008; Rand and Gardinali, 2004) 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.

6. Ecological indicators for the southwest Florida coastal wetlands

Research on attributes of the ecosystem described in Section 5 provides scientists with a detailed picture of the status and trends in the coastal wetlands; however, this level of detail is not practical for relaying information to decision-makers responsible for setting performance measures and targets for CERP. For this purpose, we present a set of ecological indicators. A number of papers have been written focusing on appropriate indicators of ecosystem function for the wetlands and estuaries of south Florida (see for example Bortone, 2005; Doren et al., 2009 and included papers in special issue; Ogden et al., 2005a and included papers). We have drawn from these papers to select the indicators proposed here and in general, followed the criteria outlined in Doren et al. (2009). The proposed indicators integrate biological, physical and ecological processes, linking together the components identified in the ICEM (Fig. 2). In addition, the indicators incorporate predictive as well as monitoring components as much as possible. These indicators are described below.

6.1. *Mangrove community structure and spatial extent*

Mangroves are the defining component of the southwest Florida coastal wetlands and as such, changes in the mangrove community are an indication of changes to other components of the ecosystem, including primary productivity, peat accretion, and habitat availability (Barnes, 2005; Davis et al., 2005; Worley, 2005). In addition, changes to the mangrove forest are related to salinity, coastal transgression, and sea level rise – all factors that need to be monitored for the entire south Florida ecosystem. A set of metrics that incorporates attributes of the mangrove community should include spatial extent, abundance and dominance of key species.

6.2. *Waterbirds*

Waterbirds use the coastal wetlands as habitat, for their food source and as rookeries; and are connected to a number of the ecological processes identified in the coastal wetlands ICEM (Fig. 2). Changes in waterbird populations, therefore, indicate changes to other components of the system, including habitat availability and diversity, trophic structure, productivity, and contaminants. Species included in the waterbird indicator are Roseate Spoonbill (*Platalea ajaja*)(Lorenz et al., 2009; Ogden et al., 2014); White Ibis (*Eudocrimas albus*) and Wood stork (*Mycteria americana*) (Frederick et al., 2009); Reddish Egret (*Egretta rufescens*), Great White Heron (*Ardea herodias occidentalis*), Brown Pelican (*Pelecanus occidentalis*), Bald Eagle (*Haliaeetus leucocephalus*), Osprey (*Pandion haliaetus*), Least Tern (*Sternula antillarum*), Lesser Scaup (*Aythya affinis*), and American Coot (*Fulica americana*) and wintering shorebirds (Ogden et al., 2014). In the south Florida ecosystem, these species are abundant, well studied, highly visible components that can move relatively easily if conditions change, making them good indicators (Stolen et al., 2005). A subset of these birds has been selected as system-wide indicators (Doren et al., 2009; Lorenz et al., 2009); thus, their use in the coastal wetlands would facilitate roll-up into a system-wide assessment. Waterbird metrics would include population size, nesting production and success, and species composition.

6.3. *Prey-base fish and macroinvertebrates*

Prey-base fish, such as sheepshead minnows (*Cyprinodon variegatus*), golden topminnows (*Fundulus chrysotus*), and rainwater killifsh (*Lucania parva*) are residents of the coastal wetlands and provide support to the higher level consumers. Their density and distribution are linked to salinity, nutrient availability, productivity, and hydroperiods (Davis et al., 2005; Lorenz, 2000; Lorenz et al., 2009), which makes them good indicators of physical components of the system. Tidal creeks may also play a role in their distribution (Davis et al., 2005). Macroinvertebrates (primarily mollusks and crustaceans) can be found in freshwater, terrestrial, estuarine and marine environments. Like the prey-base fish, they function as prey to higher consumers (Trexler and Goss, 2009), but they are also heterotrophic consumers (grazers, deposit feeders, suspension feeders and carnivores) and can play an important role in nutrient cycling (Wingard and Hudley, 2012). Select species of macroinvertebrates can be very sensitive to subtle changes in salinity and water depth (Brewster-Wingard et al., 2001; Wingard and Hudley, 2012). Because they are relatively immobile and their hard shells can aide in preservation, a record of macroinvertebrate occurrence at a particular site is preserved after their death. Utilizing prey-base fish and select species of macroinvertebrates as indicators provides information on biotic and abiotic processes of the coastal wetlands including the trophic structure, prey populations, productivity, nutrient cycling, hydroperiods, salinity, water quality, and water depth. Aquatic fauna (primarily prey-fish and macroinvertebrates) have been selected as system-wide indicators (Doren et al., 2009; Trexler and Goss, 2009), so their use in the coastal wetlands would make it possible to include these data in a system-wide assessment. Prey-fish and macroinvertebrate metrics could include spatial and seasonal differences in population densities, species composition, dominance, and size distribution.

6.4. Crocodilians

Crocodilians are “the charismatic megafauna of the Everglades. They are both the keystone and flagship species” (Mazzotti et al., 2009). The American alligator (*Alligator mississippiensis*) currently has limited nesting in the coastal wetlands although historically it was abundant in this habitat (Davis et al., 2005). Salinity is a significant factor controlling the abundance and spatial distribution of the alligator (Davis et al., 2005). The American crocodile (*Crocodylus acutus*) currently uses ponds and creeks in the mangrove estuaries of Florida Bay; however, historically it ranged northward to Vero Beach on the east coast and Tampa Bay on the west coast of Florida (Lodge, 2010), and would have been a resident of the southwest coastal wetlands. Both species are good indicators of salinity. Crocodiles are tolerant of a wide range of salinity as adults but the juveniles cannot osmoregulate and generally require salinities less than 20 ppt (Davis et al., 2005). Adult alligators tolerate some exposure to saline waters, but need to be in close proximity to freshwater ponds within the coastal zone (Davis et al., 2005). The use of crocodilians as indicators through the greater Everglades ecosystem has been documented (Mazzotti et al., 2009) because they provide information about salinity and hydrologic conditions at all stages of their life cycles. They also provide information about trophic structure of the ecosystem, diversity and productivity (Mazzotti et al., 2009). Their use as a system-wide indicator allows the information from the coastal wetlands to be rolled-up into system-wide assessments. Crocodilian indicator metrics as reported in Mazzotti et al. (2009) would include, for alligators, relative density, body condition, and occupancy rates of alligator holes; and for crocodiles juvenile growth and hatchling survival.

6.5. Periphyton

Periphyton communities in coastal wetlands form the base of the food web in the forests and marshes, and in the adjacent estuaries (Gaiser, 2009; Gaiser et al., 2005). The microalgal species contribute to soil production, and play an important role in ecosystem metabolism and nutrient cycling (Gaiser, 2009). The composition of the algal species is strongly influenced by the microenvironments of the region, nutrient availability, water quality, water availability, and salinity; and therefore can serve as indicators of changes to these components of the system (Gaiser et al., 2005). In addition, because of the short-lived nature of many periphyton species, they respond rapidly to changes in the system, especially hydrology and water quality. These attributes contribute to periphyton’s role as an indicator, particularly for rapid assessments of ecosystem health and response to perturbations. Periphyton and epiphyton are used as system-wide indicators (Doren et al., 2009), so this indicator can be linked to system-wide assessments. Periphyton indicator metrics would include periphyton abundance, quality, and community composition as discussed in Gaiser (2009).

6.6. Indicators linked to the coastal wetlands

The five indicators described above (Sections 6.1–6.5) address specific components of the southwest Florida coastal wetlands, but they also link to indicators identified for other parts of the ecosystem (Doren et al., 2009 for the greater Everglades ecosystem; Nuttle and Fletcher, 2013, for Florida’s southwest coast; Ortner et al., 2014 for SFCME). These linkages allow scientists and managers to compare and integrate information on status and trends across the ecosystem. These five ecological indicators are all dependent on the quantity, quality, and seasonality of available water and so are directly linked to the Water Column Indicators. In addition, due to the connection of the coastal wetlands to the inshore flats of the southwest Florida coast, indicators relevant to the inshore flats ICEM (Savarese, 2013) will provide information about the health of the coastal wetlands as well. These include phytoplankton blooms (Boyer et al., 2009; Rudnick et al., 2005), seagrass community structure and spatial extent (Davis et al., 2005; Madden et al., 2009), eastern oysters (*Crassostrea virginica*) (Barnes, 2005; Volety et al., 2009; Volety, 2014), West Indian manatee (*Trichechus manatus latirostris*) (Barnes, 2005), mangrove terrapin (*Malaclemys terrapin rhizophorarum*), and bottlenose dolphin (*Tursiops truncatus*) (Lorenz, 2013).

7. Summary

The coastal wetlands of the southwest coast of Florida exist at the boundary between the freshwater and marine environments and are particularly vulnerable to sea-level rise and changes in storm intensity and frequency. The impact of climate change is exacerbated by land use and water management practices and these are the natural and anthropogenic drivers that will shape the coastal wetlands in the future decades and centuries. Sustainability of the coastal transition zone is dependent upon a balance of forces and it is essential to understand how these drivers and pressures will affect the complex interaction of ecological processes that characterize the system. In addition, managers and land use planners need to understand how the ecosystem services provided by the coastal wetlands will be altered by changing drivers and pressures. The ICEM presented here illustrates these interconnections. Critical to the ecosystem health of the Everglades and the South Florida Coastal Marine Ecosystem is the role the coastal wetlands play in biodiversity, because many species spend some part of their life cycle in this habitat.

To assist management agencies in assessing the health of the system, five ecological indicators are identified that are derived from the ICEM. Mangroves are the defining species of this habitat, and therefore, mangrove community structure and spatial extent is a critical indicator of the health, status and trends in the coastal wetlands. Waterbirds are connected to many of the ecological process of the coastal wetlands and provide an indication of changes in many other components of the system. Prey-fish and macroinvertebrates are a food source for the higher level consumers and their distribution and density are linked to many other aspects of the system. Crocodilian community structure indicates current physical conditions and trophic structure of the system. Periphyton communities form the base of the food web in the coastal wetlands and give an indication of the hydrologic and nutrient conditions. These five indicators will allow scientists to provide managers with metrics that can be used to assess the coastal wetlands and that also can be rolled up into system-wide assessments for the south Florida ecosystem. Future research should focus on using new and emerging technologies, such as remote sensing techniques, to assess the health of the coastal wetlands and the impacts of change on the ecosystem services the coastal wetlands provide to society.

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