Chapter 12

Indian River Lagoon

Contributors:

Ron Brockmeyer, St. Johns River Water Management District

Kara Radabaugh and **Julie Mitchell,** Florida Fish and Wildlife Conservation Commission

Loraé Simpson, Florida Oceanographic Society

Holly Sweat, Smithsonian Marine Station

Melinda Donnelly, University of Central Florida

In

Coastal Habitat Integrated Mapping and Monitoring Program Report for the State of Florida No. 2

Edited by Kara R. Radabaugh and Ryan P. Moyer

Florida Fish and Wildlife Conservation Commission

Fish and Wildlife Research Institute

100 Eighth Avenue Southeast

St. Petersburg, Florida 33701

MyFWC.com

Technical Report No. 21, Version 2 • 2022

Chapter 12
Indian River Lagoon

Ron Brockmeyer, St. Johns River Water Management District

Kara Radabaugh and **Julie Mitchell,** Florida Fish and Wildlife Conservation Commission

Loraé Simpson, Florida Oceanographic Society

Holly Sweat, Smithsonian Marine Station

Melinda Donnelly, University of Central Florida

Description of the region

The Indian River Lagoon (IRL) system extends 156 mi (250 km) along Florida's east coast from the Ponce de Leon Inlet in Volusia County to the Jupiter Inlet in Palm Beach County. The large latitudinal extent of the IRL contributes to its high level of biodiversity, as the estuary straddles warm-temperate and equatorial climate zones (Swain et al. 1995, Kottek 2006, FDEP 2016). The IRL system consists of a series of connected coastal lagoons (Mosquito Lagoon, Banana River Lagoon, and Indian River Lagoon, Figure 12.1) bounded by barrier islands, and the St. Lucie River Estuary at the southern end (Figure 12.2). Watershed and resource management in the region is split at the boundary of Indian River and St. Lucie counties between the jurisdictions of the St. Johns River Water Management District (SJRWMD) and the South Florida Water Management District (SFWMD) (Figure 12.2). There are also five Florida Department of Environmental Protection (FDEP) aquatic preserves in the IRL system: Mosquito Lagoon, Banana River, Indian River–Malabar to Vero Beach, Indian River–Vero Beach to Fort Pierce, and Jensen Beach to Jupiter Inlet. The region also includes the Merritt Island National Wildlife Refuge, Canaveral National Seashore, Pelican Island National Wildlife Refuge, and multiple state parks.

Sandy barrier islands, dunes, and paleoshorelines run parallel to the shore, and large shell middens from indigenous people provide some local elevation (FDEP 2016). Historically, the region was in a state of natural flux due to ephemeral inlets and seasonally variable freshwater runoff. Periodic tropical cyclones reshaped barrier islands and caused inlets to open, close, or migrate (FDEP 2016). Humans have attempted to restrict and stabilize this variability with the construction of seawalls, dikes, canals, and fill. Constructed hydrologic alterations include 16 causeways, the Atlantic Intracoastal Waterway, many drainage canals, and five permanent inlets (Ponce, Sebastian, Fort Pierce, St. Lucie, and Jupiter inlets). Additionally, the Canaveral Lock connects the Banana River Lagoon with the Atlantic Ocean, and the lock-restricted C-44 canal connects the St. Lucie River with Lake Okeechobee (Figures 12.1 and 12.2).

Human population in the region grew rapidly from the 1950s through the 1970s with the expansion of tourism, the space industry, and agriculture (FDEP 2016). From 2010 to 2020, the populations of Indian River and St. Lucie counties grew by 15.8% and 18.5%, respectively, exceeding the statewide average of 14.6%. Volusia, Brevard, and Martin counties grew by 8.3–11.9% (U.S. Census 2022).

Coastal wetlands

Black needlerush (*Juncus roemerianus*) and smooth cordgrass (*Spartina alterniflora*) dominate the salt marshes found in the northern IRL (Figure 12.1), although mangroves are becoming increasingly common and less ephemeral than in the past. Mangroves and marsh succulents (*Salicornia bigelovii, Sarcocornia ambigua,* and *Batis maritima*) dominate coastal wetlands in the southern IRL (Figure 12.2, Lewis et al. 1985). Red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*), and white mangrove (*Laguncularia*

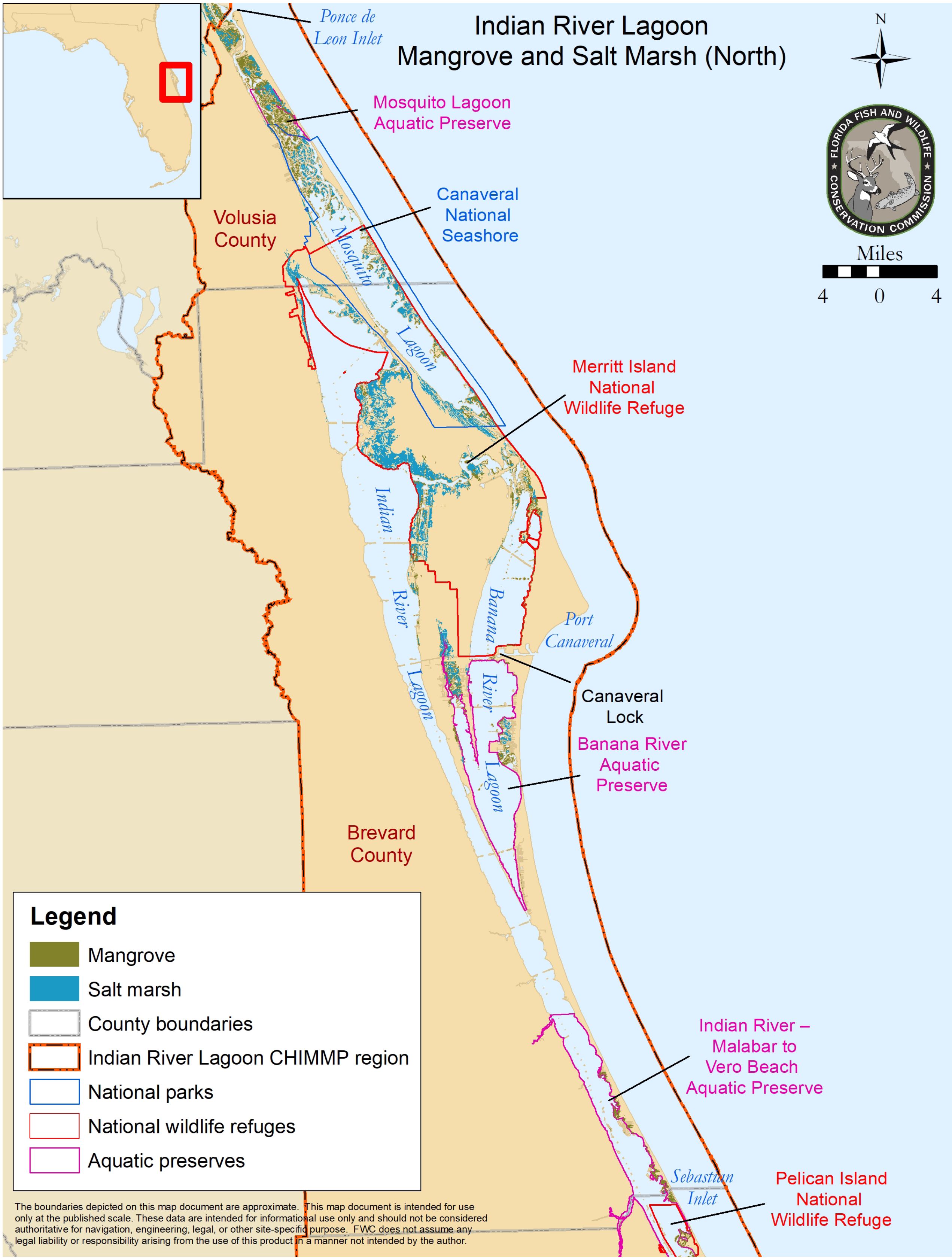

Figure 12.1. Mangrove and salt marsh extent in the northern Indian River Lagoon. Data source: SJRWMD 2014 land-use/land-cover data, based on FLUCCS classifications (FDOT 1999, SJRWMD 2019).

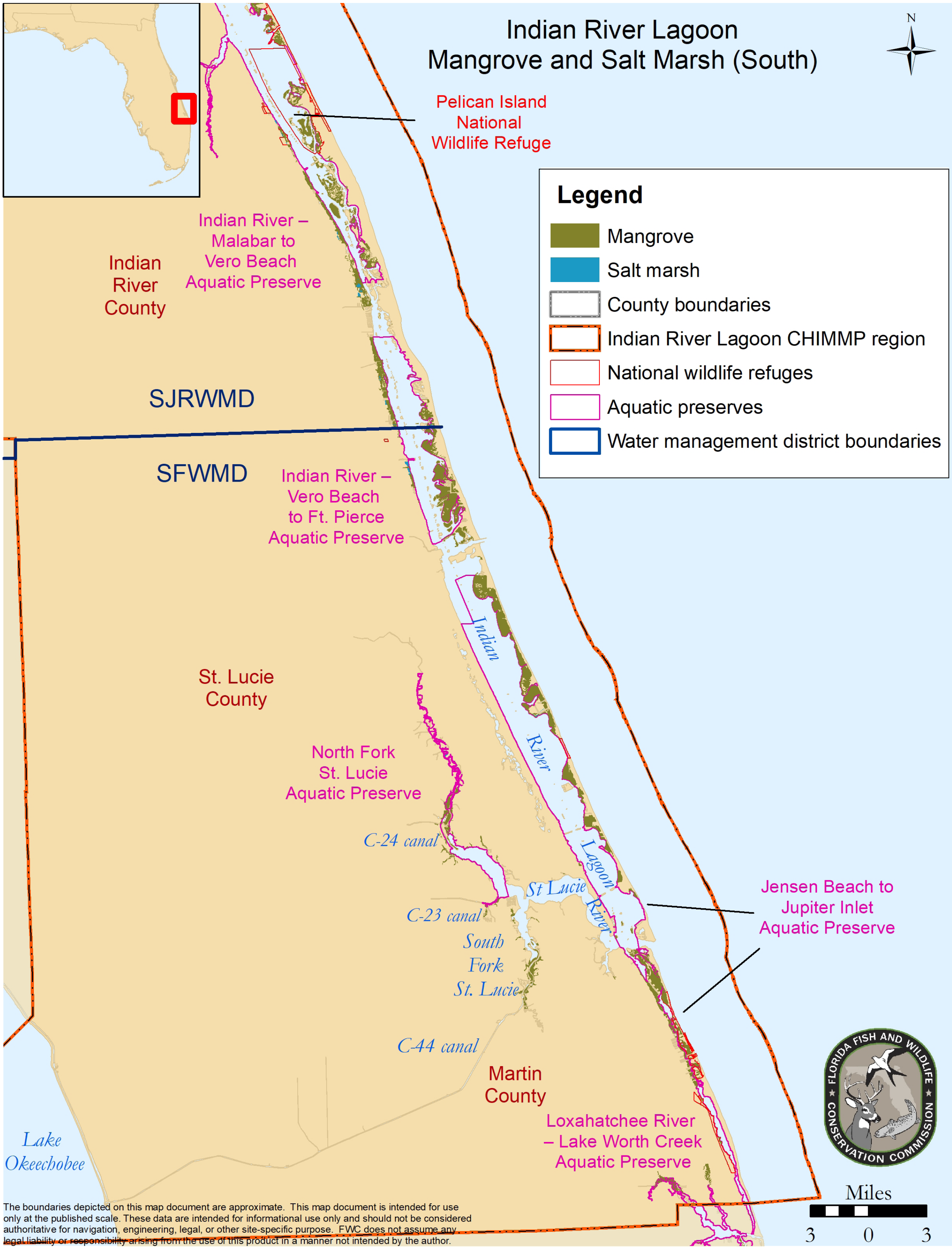

Figure 12.2. Mangrove and salt marsh extent in the southern Indian River Lagoon. Data sources: SJRWMD 2014 and SFWMD 2017–2019 land use/land cover data, based on FLUCCS classifications (FDOT 1999, SFWMD 2019, SJRWMD 2019).

Figure 12.3. Red mangrove forest at Jensen Beach in the southern Indian River Lagoon. Photo credit: Loraé Simpson.

racemosa) generally intermix rather than forming species-specific elevation zones due to the microtidal nature of much of the estuary (FDEP 2016). Buttonwood (*Conocarpus erectus*), a mangrove associate, is found at higher elevations. Mangrove species prevalence changes along the IRL latitudinal gradient, with *R. mangle* more prevalent in the southern IRL (Figure 12.3) and *A. germinans* more prevalent in the northern IRL (Simpson et al. 2017). Neighboring IRL habitats include seagrass beds and oyster reefs.

The salt marsh–mangrove ecotonal boundary is shifting northward in response to changing environmental conditions. The range and extent of mangrove forests in the region have increased significantly since the 1990s (Cavanaugh et al. 2014, Giri and Long 2014, Brockmeyer et al. 2021), which correlates with the reduction in the frequency of cold events with air temperatures less than −4°C (Cavanaugh et al. 2014). Cold-sensitive mangroves die back during freeze events or continue to expand their range if freeze events do not occur, creating a temporally and spatially dynamic ecosystem (Cavanaugh et al. 2019). In the northern IRL, salt marsh is transitioning to a mangrove-dominated plant community. Mangroves are the most common vegetation type on shorelines that lack hard-armoring in the northern IRL, particularly on gently sloped shorelines with low wave energy (Cannon et al. 2020). In addition to spreading into salt marsh habitat, mangroves have expanded onto oyster reefs in Mosquito Lagoon (McClenachan et al. 2021).

In the 1950s through the 1970s, 75–90% of the salt marshes and mangroves along the IRL were lost to development, impounded, or ditched in attempts to control the salt marsh mosquito population (Taylor 2012, Brockmeyer et al. 2021). These impoundments were generally created using dragline excavators (Figure 12.4). During this process, sediment was removed from an adjacent parallel ditch and used to create an impoundment, effectively isolating coastal wetlands from neighboring marshes and tidal flow. Approximately 16,200 ha (40,000 ac) of coastal wetland were impounded in the IRL (Brockmeyer et al. 1997). Dragline ditches (Figure

Figure 12.4. Construction of the last impoundment along the IRL in 1974 for the control of salt marsh mosquitoes using the typical dragline excavator. The Gumbo Limbo Island impoundment was the first and only impoundment along the IRL built purposefully for rotational impoundment management. Photo courtesy of the Florida Medical Entomology Laboratory Archives.

12.4), networks of deep ditches and spoil piles, were also used to combat mosquitoes. These ditches were open to tidal flushing, but the higher elevation of the adjacent spoil piles facilitated the establishment of invasive vegetation such as Brazilian pepper (*Schinus terebinthifolia*) and Australian pine (*Casuarina equisetifolia*). Approximately 810 ha (2,000 ac) of coastal wetlands were impacted by ditching with draglines (Rey et al. 2012). The impoundment and ditching of salt marshes and the accompanying hydrologic alteration likely promoted mangroves at the expense of the historically abundant marsh succulents in many areas.

Recent and ongoing efforts by SFWMD, SJRWMD, the Merritt Island National Wildlife Refuge, and county mosquito control districts to mitigate and restore impoundment hydrology focus on installing culverts through the impoundments. Rotational impoundment management is now used in much of the region, allowing seasonal connection to the estuary while continuing to control mosquito populations (Clements and Rogers 1964, Brockmeyer et al. 1997, Taylor 2012). In this process, the wetlands are isolated and flooded via pumps during the mosquitoes' summer breeding season (approximately May–October) and are left open to the estuary the remainder of the year. This management option has been found to improve water quality, plant diversity, and fish movement (Rey et al. 1990, Brockmeyer et al. 1997).

Approximately 80% of the impounded wetlands have been reconnected either seasonally or permanently (FDEP 2016). Approximately 17% of impounded wetlands still need some level of rehabilitation, but around 2% of impounded wetlands remain isolated because they are surrounded by rocket-launch facilities, power plants, or other developed areas, making them incompatible with reconnection (IRLNEP 2019). Wetland reconnection and restoration are a major part of the Surface Water Improvement and Management Plan (SWIM) for the IRL (SJRWMD and SFWMD 2002). Other efforts include preserving wetlands through land acquisition, planting native species, and removing invasive species (SJRWMD and SFWMD 2002).

Figure 12.5. Vegetation along the St. Lucie River includes red mangroves (*Rhizophora mangle*) and smooth cordgrass (*Spartina alterniflora*) (top). Red mangrove is found mixed with a variety of other vegetation (bottom), including the red maple (*Acer rubrum,* in the middle of the image) and the giant leather fern (*Acrostichum danaeifolium,* at far right). Photo credits: Julie Mitchell (top) and Holly Sweat.

Hydrology and water quality

Historically, the IRL drainage basin was much smaller, and its boundary followed the Atlantic Coastal Ridge. Numerous canals were constructed from 1916 through the 1950s to drain much of the adjacent wetlands for agriculture (primarily for cattle ranging and citrus orchards). These canals greatly increased both the size of the IRL watershed and the rate at which water was delivered to the lagoon. The canals increased freshwater flow in the rainy season, concentrating stormwater runoff and dumping large quantities of freshwater and associated land pollutants into the lagoon (FDEP 2016). In the SJRWMD, the original Upper St. Johns River Basin, the C-1 Rediversion and other projects have moved substantial freshwater flows away from the IRL and back to the St. Johns River (https://www.sjrwmd.com/waterways/st-johns-river/upper/). Overall flow in the dry season has decreased due to agricultural and urban consumption. The lagoons receive freshwater input from surface runoff and groundwater seepage, as well as minor inputs from precipitation and natural tributaries. In the 1960s and 1970s, poorly treated wastewater was discharged into the IRL, resulting in poor water quality in the system, particularly near urban centers (FDEP 2016). These discharges were mostly removed under the Indian River Lagoon System and Basin Act of 1990 (Chapter 90-262, Laws of Florida), though issues remain. Septic systems are still widely used in much of the area, and seepage of bacteria, phosphorus, and nitrogen from old systems that are not properly maintained are of particular concern (FDEP 2009a).

Groundwater sources in the region include the Floridan Aquifer, intermediate aquifer, and surficial aquifer. The Floridan Aquifer and the surficial aquifer are used for agricultural and public water supplies, although the Floridan Aquifer becomes brackish in the southern IRL. The SJRWMD and SFWMD have reduced permitted withdrawals from the surficial aquifer in an attempt to protect wetlands and prevent saltwater intrusion (FDEP 2016).

The barrier islands that border the east side of Mosquito Lagoon, Banana River Lagoon, and IRL have few and widely spaced inlets. This restricts tidal flushing and currents, resulting in high water-residence times and making the region susceptible to impaired water quality (FDEP 2009a, 2009b, 2016). Water-level changes in the Mosquito Lagoon are generally driven by wind more than by tidal currents or rainfall (FDEP 2009a). The Banana River Lagoon requires two years for complete flushing, while flushing in the southern IRL is 10–15 times more rapid than in the northern lagoons (FDEP 2009b, FDEP 2013, FDEP 2016). In extreme summer drought conditions, evaporation, limited freshwater input, and limited flushing have caused salinity values as high as 45 on the practical salinity scale in the Banana River Lagoon and parts of the northern IRL and southern Mosquito Lagoon (FDEP 2016). The average depth of the IRL is 4 ft (1.2 m); the water quickly warms in the summer, decreasing dissolved oxygen and facilitating the development of hypoxic or anoxic conditions (FDEP 2016). In 2010–2013, phytoplankton blooms resulted in extensive losses of seagrass in the IRL (SJRWMD et al. 2012, Morris et al. 2022). The region also had unusual mortality events in July 2012 and April 2013, with extensive deaths of dolphins, manatees, and brown pelicans (FDEP 2016). More recently, seagrass loss was determined to be a primary driver of the 2021–2022 manatee unusual mortality event. Research into the ecosystem-wide relationships that led to these algal blooms, seagrass losses, and mortality events are at the forefront of scientific and management efforts in the region (SJRWMD et al. 2012; Morris et al. 2022).

St. Lucie Estuary

The St. Lucie Estuary (SLE), which connects to the southern IRL, was a freshwater river until the St. Lucie Inlet was dug in 1892, resulting in saltwater intrusion up to 26 km (16 mi) away at Midway Road in Fort Pierce (FDEP 2009c). Construction of the St. Lucie Canal (C-44 Canal; Figure 12.2) was completed in the 1920s, draining large areas west of the SLE and connecting water flow from Lake Okeechobee to the south fork of the SLE (FDEP 2016). These freshwater inputs drastically increased the sediment and nutrient load to the SLE. Depending on the duration and magnitude of freshwater releases from Lake Okeechobee, the estuarine salinity may become oligohaline, stressing or killing estuarine plants and animals (FDEP 2016). The Lake Okeechobee Watershed Project and IRL South Feasibility Plan components of the Comprehensive Everglades Restoration Plan (CERP) emphasize decreasing the number and volume of large freshwater discharges from Lake Okeechobee into the SLE (Bartell et al. 2004, CERP 2013, RECOVER 2020a, 2020b). The SWIM plan for the IRL, including the SLE, is also focused on improving the quality of water entering the system (SJRWMD and SFWMD 2002).

The North Fork St. Lucie River was dredged and bermed for flood control and agriculture from the 1920s to the 1940s (FDEP 2009c). This dredging straightened the river and isolated much of the flood plain and the oxbows from the main river channel, resulting in a faster-flowing river channel, with regions of stagnation and sedimentation in the former oxbows (FDEP 2009c). The North Fork was connected to the C-23/C-24 canal system in the 1950s as a part of the Central and Southern Florida Project, further increasing the amount of freshwater diverted into the SLE (SFWMD 2009a). Tidal wetlands and mangrove forests along the SLE are dominated by red mangrove (Figure 12.5), with minor contributions from giant leather fern (*Acrostichum danaeifolium*) and coastal plain willow (*Salix caroliniana*) (FDEP 2009c). Brazilian pepper and Australian pine have overtaken much of the mangrove habitat on the North Fork St. Lucie River, in part due to the straightening of the river channel (FDEP 2009c). A portion of the IRL South Feasibility Plan includes reconnecting isolated oxbows along the North Fork to improve water filtration and habitat utilization in the remnant floodplain communities (Bartell et al. 2004).

Threats to coastal wetlands

- **Hydrologic alteration:** The hydrology of the IRL system has been significantly altered by the construction of drainage canals and connection of the SLE to Lake Okeechobee, increasing both the size of the watershed and the rate of surface water delivery. Remaining impoundments and dragline ditching also decreased the functionality of coastal wetlands, hindering their ability to improve the quality of surface water.
- **Nutrient loading and poor water quality:** The combination of altered watershed hydrology, increased freshwater inflow, polluted runoff, loss of wetlands, and low flushing make the IRL highly susceptible to impaired water quality. The buildup of pollutants, strong temperature changes, hypoxic conditions, and algal blooms have ecosystem-wide impacts on the estuary. Nutrient loading can alter mangrove growth and function, which can reduce resilience and recoverability of mangroves impacted by environmental stressors (e.g., droughts and hurricanes) (Lovelock et al. 2009, Feller et al. 2015).
- **Urban development:** The rate of urban development and the draining of wetlands surrounding the IRL have slowed since their peak in the 1950s to the 1970s, but the population continues to grow, and some of the remaining impounded coastal wetlands remain in private ownership. This limits restoration efforts, and these wetlands are still vulnerable to development (IRLNEP 2008). Additionally, developed land cannot accommodate landward migration of coastal wetlands under sea-level-rise scenarios, resulting in the reduction or disappearance of these important coastal habitats (e.g., Rogers 2021).
- **Sea-level rise and climate change:** Sea-level rise has been established as a threat to coastal zones for decades (Nicholls and Cazenave 2010). To persist, wetland ecosystems must adjust to rising sea level by building substrate vertically or migrating landward, or they face becoming submerged. Wetland extent will likely decline in regions of urban development that lack appropriate buffer-zone habitat (IRLNEP 2008). Due to the decrease in frequency and severity of major freeze events, mangroves have expanded into salt marsh and other adjacent habitats (Cavanaugh et al. 2014). If cold events continue to be infrequent, this pattern will likely result in continued expansion of mangroves into salt marsh habitat (Cavanaugh et al. 2019).
- **Invasive vegetation:** Invasive vegetation, most notably Brazilian pepper and Australian pine, encroaches on the edges of coastal wetland habitat, particularly on impoundments or on spoil islands (FDEP 2016) and outcompetes the native vegetation. Brazilian pepper is particularly prevalent along dragline ditches and on the bermed and straightened portions of the North Fork St. Lucie Estuary (FDEP 2009c). Also, native species such as red cedar (*Juniperus virginiana*) and saltwater false willow (*Baccharis angustifolia*) have colonized these areas of high ground, and thus woody species now inhabit regions of the marshes historically dominated by herbaceous vegetation.

Mapping and monitoring efforts

Water management district mapping

Since 1990 SJRWMD has conducted regular land-use/land-cover (LULC) sampling using aerial orthophotography. These mapping efforts also used wetland assessments from the late 1980s with the assumption that regions identified as wetlands were still wetlands if they had not been developed. Exceptions occurred in areas in which wetlands had been drained or experienced prolonged dry conditions. Updates were made to the 2009 LULC maps using 2013–2016 digital orthophotography to create the 2014 LULC map shown in Figures 12.1 and 12.2 (SJRWMD 2019). The minimum mapping unit for wetlands was 0.2 ha (0.5 ac). Land features were categorized according to the Florida Land Use and Cover Classification System (FLUCCS) (FDOT 1999) and outlined in the SJRWMD photointerpretation key (SJRWMD 2018). Salt marsh and mangrove extent in the IRL region according to past and present SJRWMD and SFWMD LULC maps is shown in Figure 12.6 and Table 12.1. Land cover extent published in 1990 and 1995 is excluded from Figure 12.6, because mapped changes in land cover are largely due to variable mapping methods (e.g., classification of ponds or marshes with cattails has changed over time) rather than true changes in land cover.

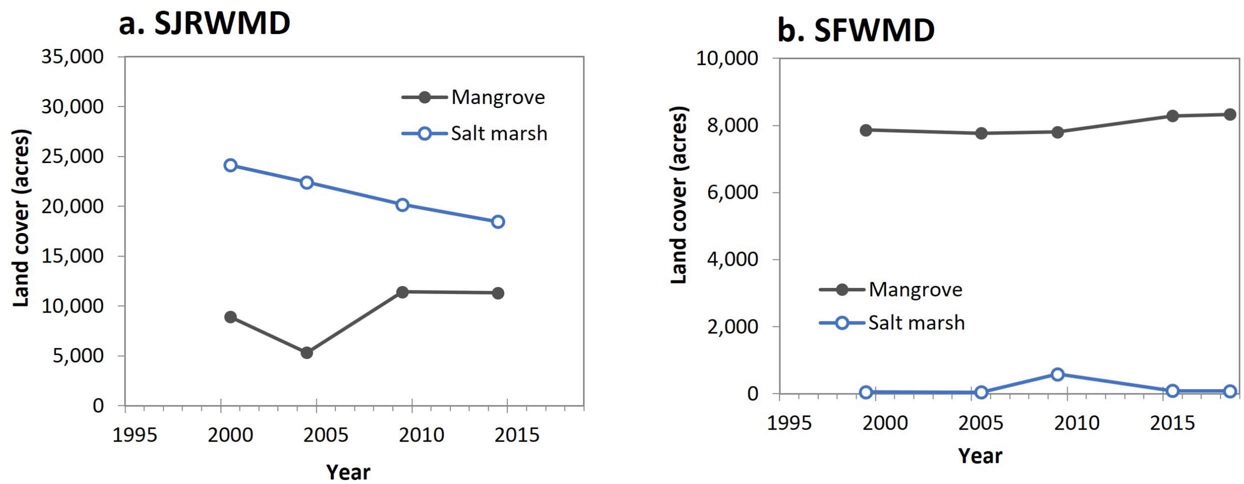

Figure 12.6. Extent of salt marsh and mangrove swamp in land-use/land-cover maps from the two water management districts in the Indian River Lagoon region (SJRWMD 2019, SFWMD 2019). Data from 1990 and 1995 are excluded due to variable mapping methods.

The SFWMD has updated its LULC mapping every 3–5 years since 1995. Land-cover classifications are based upon SFWMD's modifications to FLUCCS (FDOT 1999, SFWMD 2009b). Figure 12.2 presents data from 2017–2019 surveys (SFWMD 2019). Minimum mapping units were 0.2 ha (0.5 ac) for wetlands. Maps were made by interpreting aerial photography and updating 2014–2016 LULC maps. Some changes in land-cover area, such as the increase in salt marsh area in 2008–2009 (Figure 12.6, Table 12.1), may reflect changes in mapping methods.

Table 12.1. Extent of mangrove swamps (FLUCCS 6120) and salt marshes (FLUCCS 6420) in the Indian River Lagoon region. Data sources SJRWMD (2019) and SFWMD (2019).

District/year of LULC map	Salt marsh (ha)	Salt marsh (ac)	Mangrove (ha)	Mangrove (ac)
SJRWMD				
1990*	7,743	19,133	3,602	8,902
1995*	4,301	10,628	2,153	5,321
2000	9,766	24,132	4,621	11,418
2004	9,071	22,414	4,586	11,332
2009	8,166	20,179	5,678	14,030
2014	7,467	18,452	5,939	14,677
SFWMD				
1995*	4	10	3,516	8,688
1999	20	49	3,182	7,863
2004–2005	17	42	3,142	7,765
2008–2009*	235	581	3,159	7,806
2014–2016	34	85	3,353	8,286
2017–2019	33	80	3,370	8,328

* Changes in land cover are also affected by variable mapping methods.

Shoreline characterization in northern Indian River Lagoon

The University of Central Florida (UCF) mapped shoreline characteristics of Mosquito Lagoon, Banana River, and northern Indian River Lagoon in Brevard County using methods developed by SJRWMD for north Florida. Beginning in 2015, UCF evaluated a total of 375 miles of shoreline in the northern IRL, from Ponce Inlet (Volusia County) to Sebastian Inlet (Brevard County), with support from the City of Titusville, Brevard County Natural Resources, and the Florida Fish and Wildlife Conservation Commission (FWC). Shoreline evaluations were completed at transects located every 30 m in developed areas and every 100 m of shoreline in undeveloped areas, with transect spacing based on frequency of transitions to different habitats or armoring type. Data collected on each transect included presence and type of hard structure, adjacent property use, slope, width of each habitat type and the intertidal zone, plant species in each habitat type, presence of oysters and seagrass, and severity of erosion.

Data and analyses have been used to identify locations needing restoration and to guide decision-making for shoreline management. Results indicated extensive hard-armoring in Brevard County, with 67% of shorelines hard-armored (Donnelly et al. 2018). In comparison, only 11% of Mosquito Lagoon shorelines were hard-armored because the majority of property is located in the Canaveral National Seashore, Merritt Island National Wildlife

Figure 12.7. Restored salt marsh at New Smyrna Beach, on property belonging to the Florida Fish and Wildlife Conservation Commission. The image at left is immediately following restoration in 2015; the image at right shows vegetation growth in 2021. Photo credits: SJRWMD.

Refuge, or the Mosquito Lagoon Aquatic Preserve (Kibler et al. 2020). Shoreline characterization was used to develop hydrodynamic thresholds for mangroves and to prioritize shorelines for stabilization and restoration efforts (Cannon et al. 2020). Shoreline profile data are publicly available through the UCF repository: https://stars.library.ucf.edu/ceelab-researchdata/1/ and https://stars.library.ucf.edu/shorelines/1/. Funding was received to expand shoreline characterization into the southern Indian River Lagoon beginning in 2022.

Habitat restoration, rehabilitation, and monitoring in northern IRL

- **Salt marsh restoration at New Smyrna Beach:** In 2014, the FWC and SJRWMD partnered with NOAA and the Marine Discovery Center, a nonprofit education and research facility, in New Smyrna Beach to restore 2 ha (5 ac) of salt marsh adjacent to the center. Restoration activities included excavation and removal of dredged spoil and subsequent marsh planting, as well as creation of a living shoreline for demonstrating alternative shoreline stabilization techniques (Figure 12.7). The site serves as a hub for regional restoration, supporting numerous programs for monitoring and research in conjunction with the Marine Discovery Center and serving as a donor marsh, which supplies plants for restoration projects throughout the region.
- **Hydrologic restoration of coastal wetland altered for mosquito management:** Beginning in the 1990s, the U.S. Fish and Wildlife Service, SJRWMD, and Volusia County Mosquito Control worked to restore and rehabilitate salt marsh in the northern IRL that had been impacted by the mosquito control methods of impounding and ditching (Brockmeyer et al. 2021). Restoration involved leveling impoundment dikes or spoil piles created by mosquito ditching and partly filling adjacent borrow ditches to return habitat to natural marsh elevations (Figure 12.8), re-establishing hydrological conditions, and initiating natural regeneration of wetland communities. Initial monitoring efforts to evaluate the effectiveness of impoundment restoration methods began in 2005 at three restored impoundments and two reference marshes. Monitored parameters included abiotic characteristics related to natural wetland hydrology (elevation, soil moisture, soil salinity) and changes in biotic characteristics (plants, fiddler crabs). Results of the first phase of monitoring identified halophytic vegetation along dike shorelines that could be conserved during leveling and target elevations to limit nonnative species recruitment postrestoration; these recommendations were applied to dike removal begin-

Figure 12.8. Coastal wetlands in Mosquito Lagoon that were ditched with a dragline in the late 1960s to control mosquitoes. The foreground shows the results of the original ditching; restoration is under way in the center of the image. Photo credit: Linda Walters, University of Central Florida.

ning in 2007. Postrestoration monitoring through 2012 documented how the conservation of shoreline vegetation increased the rate of plant community recovery by providing a source of native wetland plants directly adjacent to restored habitat and prevented recruitment of nonnative plants, including Brazilian pepper (Brockmeyer et al. 2021). Additional monitoring was completed between 2015 and 2017 at 20 impoundments, ranging from 5 to 18 years postrestoration, and at restored dragline-impacted wetlands in 2019 and 2020, 9 to 10 years postrestoration, to evaluate long-term changes in abiotic and biotic characteristics. Results showed that hydrological restoration of mosquito impoundments supported the development of functional wetland ecosystems and reversed some of the extensive habitat loss caused by alterations for mosquito management.

- **Living shoreline stabilization in Canaveral National Seashore:** Living shoreline stabilization and monitoring in Mosquito Lagoon began in 2011 through a partnership between UCF, the Southeast Archeological Center (U.S. National Park Service), and Canaveral National Seashore (Donnelly et al. 2017). The purpose of this project was to develop living shoreline methods for protecting historical structures (e.g., shell middens, houses) threatened by shoreline erosion and sea-level rise. After experimental testing, stabilization methods mimicked natural shorelines and included a combination of oyster materials (shell mats or bags for recruiting oysters), smooth cordgrass, and juvenile mangroves. Since 2011, a total of 4.2 km (2.6 mi) of shoreline has been stabilized in Mosquito Lagoon at 13 historically significant shell midden locations using living shoreline methods. This project combined science-based restoration with education and outreach components for students from preschool through college and thousands of community volunteers. Funding and in-kind support were provided by the Indian River Lagoon National Estuary Program, the FWC, the Marine Discovery Center's Shuck-and-Share program, and the Coastal Conservation Association.

  Pre- and poststabilization monitoring protocols evaluated severity of erosion, characterized habitat structure, and documented diversity and abundance of plants and mobile and sessile marine invertebrates.

Permanent monitoring transects were established at living shorelines and nearby eroding and noneroding shorelines as experimental controls. All locations were monitored seasonally during the first year poststabilization and then annually to document long-term changes following stabilization. By 2021, all sites completed in 2019 or earlier had reached at least 90% cover of vegetation in the intertidal areas planted with mangroves and smooth cordgrass. The first shell midden shoreline stabilized at Turtle Mound was fully vegetated with mature mangroves up to 4 m in height after 10 years. Oysters have recruited to breakwater structures at all locations. Stabilization has also supported seagrass in adjacent subtidal areas, and increased seagrass density has been observed at 8 of 13 locations where stabilization has occurred. Ongoing monitoring at control shorelines has documented increased density of mangroves at all locations since 2011. Living shoreline sites have been evaluated by additional shorter-term monitoring efforts, documenting effects of mangrove size and breakwaters for mangrove survival (Fillyaw et al. 2021), bird and mammal diversity and behavior (Rifenberg et al. 2021), and changes in fish communities (Loch et al. 2021). Living shorelines installed in 2020–2021 focused on testing the use of nonplastic materials for breakwater structures, and monitoring is ongoing to evaluate integrity and effectiveness of materials used in Mosquito Lagoon.

IRL mangrove permanent plot monitoring

In 2014, permanent mangrove monitoring plots were established by the Smithsonian Environmental Research Center along the Indian River Lagoon and Mosquito Lagoon. Long-term monitoring at these sites includes mangrove and salt marsh biomass and edaphic factors (see Simpson et al. 2017 for methods). Additionally, the sites have been used to monitor carbon storage, soil efflux (Simpson et al. 2019), decomposition and epifaunal abundance (Smith et al. 2019), and black mangrove genetic differentiation (Kennedy et al. 2020). The permanent plots were established as a baseline for future monitoring, especially considering disturbance and global climate change drivers. Ongoing monitoring is conducted by the Florida Oceanographic Society.

Jensen Beach restoration monitoring

In late 2021, the FWC and the Florida Oceanographic Society began a project designed to monitor tree mortality and recovery in an impounded mangrove forest in Jensen Beach. The Jensen Beach Impoundment is a 70-ha (170 ac) impounded mangrove wetland that was created for mosquito control. The forest was chronically stressed by limited hydrologic flow, and after Hurricane Irma in 2017 it experienced massive vegetation mortality in 54 acres following acute stress caused by standing water. This project is monitoring the water quality, hydrology, forest elevation, vegetation, and soil in areas that show signs of low, moderate, and severe stress within the impounded wetland. Monitoring will continue after restoration of the forest to evaluate forest recovery following the addition of culverts (completed in 2022) and clearing of ditches (scheduled for 2023) to improve water flow.

Southern IRL and St. Lucie Estuary infaunal and environmental monitoring

As part of CERP, the Smithsonian Marine Station has monitored benthic infaunal communities in relation to changing water quality and sediment characteristics at 15 sites in the southern IRL and SLE quarterly since 2005 (Sweat et al. 2021). Infauna (e.g., burrowing worms, mollusks, and crustaceans) perform important ecosystem services, including consuming settled and suspended organic matter (Word 1979, Tenore et al. 2006), aerating and cycling nutrients in sediments (Rysgaard et al. 1995, Mermillod-Blondin et al. 2004), and serving as prey for higher-level organisms (Virnstein 1977, Seitz et al. 2001). These communities are also excellent indicators of habitat quality because they are relatively stationary and more sensitive to stressors than larger, more mobile taxa. As such, infauna have been monitored as benchmarks of environmental change in Florida estuaries for decades (e.g., Bloom et al. 1972, Lewis 1984, Mason et al. 1994, McRae and Madley 2001, Walton et al. 2013).

Four of the 15 sites are in mangrove habitat (Figure 12.9), representing different salinity regimes, sediment characteristics, and impacts from inland runoff and coastal tidal exchange. This habitat diversity is reflected in the composition of the infauna. Sites in the north and south forks of the St. Lucie River (M01, M02, and M14) are characterized by muddy sediments and are impacted by inland freshwater. The communities at these sites are dominated by fresh and brackish taxa tolerant of environmental disturbance. Located near the St. Lucie Inlet, M08 is more saline, with sandier sediments and no mud. This site hosts more diverse infaunal communities that contain species sensitive to disturbance (e.g., the snail *Acteocina canaliculata,* Figure 12.9, bottom right, middle photograph).

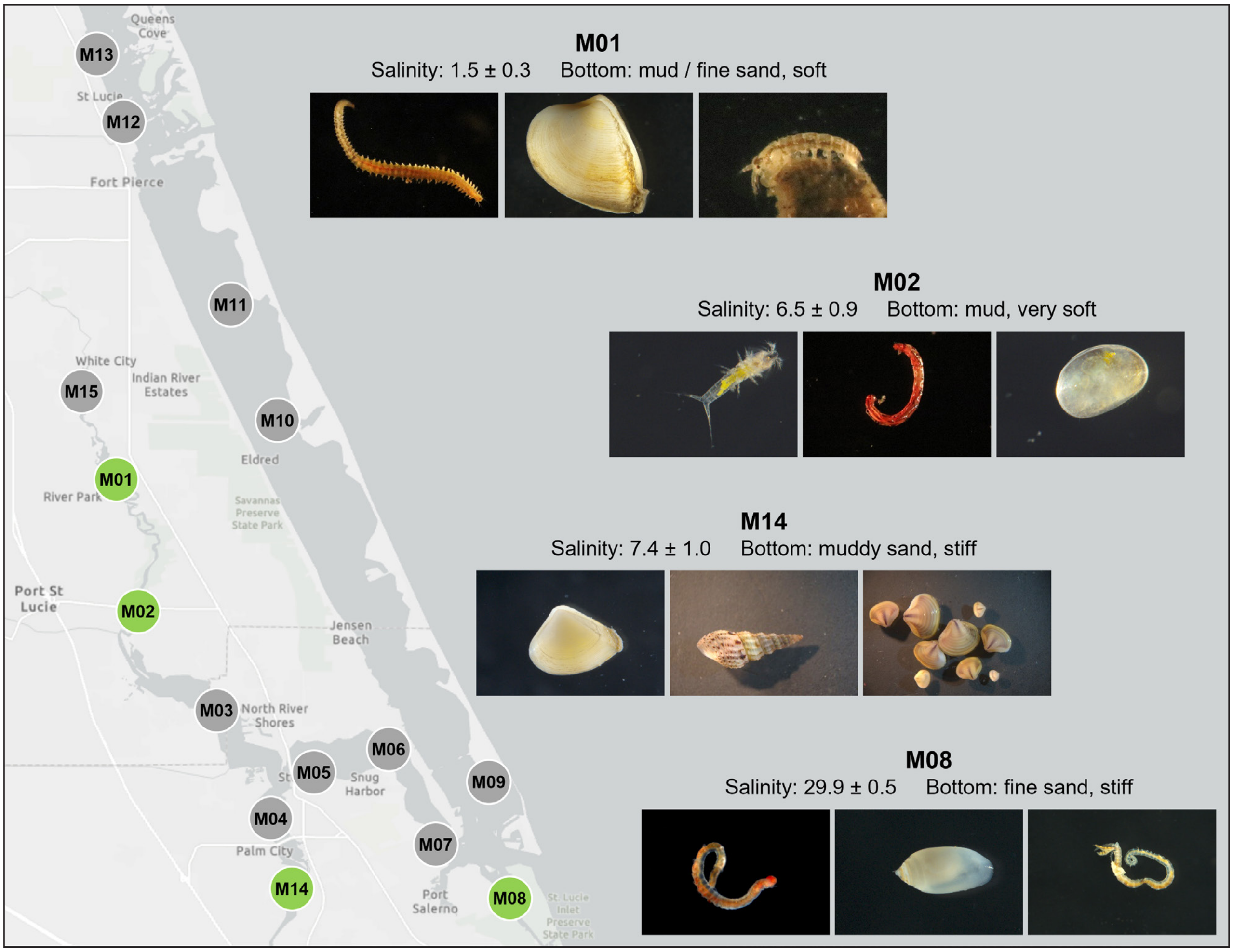

Figure 12.9. Map of 15 long-term infaunal monitoring sites in the southern IRL and SLE, 4 of them in mangroves (green). Insets present salinity and bottom type and depict characteristic benthic taxa from the mangrove sites. Photographs (left to right): **M01,** *Laeonereis* sp., *Rangia cuneata,* tanaid crustacean; **M02,** harpacticoid copepod, chironomid midge larva, sarsiellid ostracod; **M14,** *Mulinia lateralis, Melanoides tuberculata, Corbicula* sp.; **M08:** *Mediomastus californiensis, Acteocina canaliculata, Streblospio benedicti.*

North Fork St. Lucie River Floodplain vegetation study

In 2009, four transects were established through vegetation in the North Fork St. Lucie River floodplain in a study of canopy, shrub, and ground-cover communities in conjunction with soil conductivity and soil moisture (SFWMD 2015). This research was a cooperative effort between the Coastal Ecosystems Section of SFWMD, FDEP's Florida Park Service at the Savannas Preserve State Park, and the FDEP IRL Aquatic Preserve office. The results of the survey indicated that most of the remaining floodplain consisted of hammock and bottomland hardwood communities (SFWMD 2015). Swamp communities had been limited by the placement of spoil material along much of the shoreline and at the openings of several oxbows. Most of what remains of the floodplain suffers from reduced hydroperiods. Saltwater intrusion was evidenced by the higher soil conductivity values downstream, in areas dominated by white mangroves. Water managers are examining means of restoring upstream freshwater inflow and enhancing the floodplain habitat for fish and wildlife as CERP plans are implemented and adaptive management decisions are made.

North Fork St. Lucie River mangrove mapping

St. Lucie County Environmental Resources Department mapped the extent of mangroves along the North Fork St. Lucie River from Port St. Lucie Boulevard northward to the fork of Ten Mile Creek and Five Mile Creek during January–February 2013 (Figure 12.10). Observations were made on intensive shoreline scouting trips, primarily by boat but also by land. Nearly all mangroves observed were red mangroves, with a few black mangroves at the southern end. Heights of some isolated trees were also recorded.

Recommendations for protection, management, and monitoring

- Continue efforts toward hydrologic reconnection by installing culverts through impoundment dikes (IRLNEP 2019). This improves hydrologic flow and enables aquatic species to travel between lagoon and wetland habitats (Brockmeyer et al. 1997, IRLNEP 2008). Where practical, fully restore impoundments by returning dike material to the borrow ditch and grading to adjacent wetland elevation (Rey et al. 2012, Brockmeyer et al. 2021). Likewise, continue restoration of areas with dragline ditches and spoil piles to re-establish more natural wetland elevations. Continue to monitor and evaluate restored wetlands to improve and increase ecosystem services.
- Encourage wetland protection, restoration, and management on private lands and minimize further loss of wetlands through acquisition of privately owned wetlands and ordinances (IRLNEP 2008, 2019, Rey et al. 2012). Full implementation of the Indian River Lagoon Blueway Florida Forever Project would be a major step in this effort (FDEP 2020).
- Continue installation of living shorelines with native plants, which helps prevent erosion, stabilize shores, and improve water quality (FDEP 2016, IRLNEP 2019). Nutrient reduction and improvement of water quality are focus areas in many IRL management plans; coastal wetlands serve as vegetative buffers and assist in achieving these goals (SJRWMD and SFWMD 2002, BMAP 2013, FDEP 2016).
- Support long-term monitoring of coastal wetland restoration and living-shoreline sites to guide future projects and provide data for better understanding trends in ecosystem structure and function.
- The susceptibility of the IRL ecosystem to water quality issues, algal blooms, and subsequent unusual mortality events highlights the need for further study to more fully elucidate cause-and-effect relationships in the ecosystem.
- The water quality of the SLE is tightly linked to freshwater releases from Lake Okeechobee. Freshwater releases should be managed to reduce the frequency and duration of extreme salinity events and high nutrient and sediment loads into the SLE (SJRWMD and SFWMD 2002, RECOVER 2020a, 2020b).

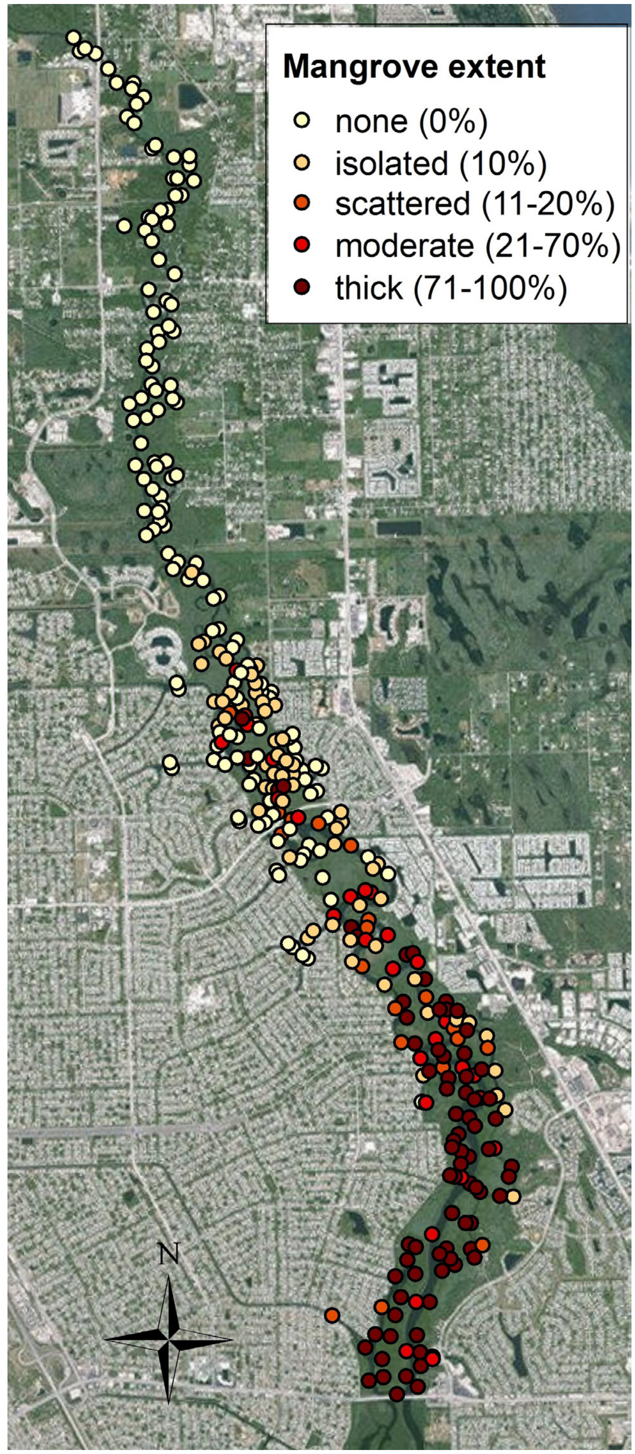

Figure 12.10. Density of mangroves along the North Fork St. Lucie River in 2013.

- As a part of urban planning, establish or enhance upland buffers along coastal wetlands to enable shoreward migration of coastal vegetation in the face of sea-level rise (IRLNEP 2008). Where needed, restore a natural gradient by removing dikes or berms between wetlands and adjacent uplands. Further research is also recommended to determine best ecosystem-level management practices in the face of changing coastal conditions (IRLNEP 2008).

- Continue efforts to remove invasive nonnative plants and to encourage or plant native species. Restoration efforts that re-establish proper wetland elevations facilitate recolonization by native coastal wetland plants. Educate residents about invasive vegetation and continue efforts to rapidly recognize and address new invasive species.

Acknowledgments

The first version of this chapter was written by Ron Brockmeyer, Jeff Beal, Brian Sharpe, Marion Hedgepeth, John Tucker, Hyun Jung Cho, Christina Powell, and Kara Radabaugh for the Coastal Habitat Integrated Mapping and Monitoring Program Report for the State of Florida, version 1, published in 2019. Version 1 geographic information system (GIS) support was provided by Christi Santi; Version 2 acreage updates were calculated by LaTosha Thompson. Technical review was completed by Caroline Gorga (version 2) and Amber Whittle and Shannon Whaley (version 1). Scientific and copy review of versions 1 and 2 was completed by Bland Crowder; additional copy review of version 2 was provided by Savanna Hearne and Adrienne Ruga. The Coastal Habitat Integrated Mapping and Monitoring Program is funded by the Florida Fish and Wildlife Conservation Commission, Florida's Wildlife Legacy Initiative, and the U.S. Fish and Wildlife Service's funding support of Florida's State Wildlife Grants Program (award number F21AF01383).

Works cited

Bartell SM, Burns JJ, Fontane DG, McAnally WH, et al. 2004. Independent scientific review of the Indian River Lagoon – South Project Implementation Report.

Bloom SA, Simon JL, Hunter VD. 1972. Animal–sediment relations and community analysis of a Florida estuary. Mar Biol. 13:43–56.

BMAP (Basin Management Action Plan). 2013. Basin management action plan for the implementation of total maximum daily loads for nutrients in the Indian River Lagoon basin central Indian River Lagoon. Tallahassee, FL: Florida Department of Environmental Protection and the Central Indian River Lagoon Stakeholders. Available from https://floridadep.gov/sites/default/files/central-irl-bmap.pdf.

Brockmeyer RE, Donnelly M, Rey JR, Carlson DB. 2021. Manipulating, managing and rehabilitating mangrove-dominated wetlands along Florida's east coast (USA): balancing mosquito control and ecological values. Wetl Ecol Manag. 30:987–1005.

Brockmeyer RE, Rey JR, Virnstein RW, Gilmore RG, Earnest L. 1997. Rehabilitation of impounded estuarine wetlands by hydrologic reconnection to the Indian River Lagoon, Florida. Wetl Ecol Manag. 4:93–109.

Cannon D, Kibler K, Donnelly M, McClenachan G, et al. 2020. Hydrodynamic habitat thresholds for mangrove vegetation on the shorelines of a microtidal estuarine lagoon. Ecol Eng. 158:106070.

Cavanaugh KC, Dangremond EM, Doughty CL, Williams AP, et al. 2019. Climate-driven regime shifts in a mangrove–salt marsh ecotone over the past 250 years. PNAS. 116(43):21602–21608.

Cavanaugh KC, Kellner JR, Forde AJ, Gruner DS, et al. 2014. Poleward expansion of mangroves is a threshold response to decreased frequency of extreme cold events. PNAS. 111:723–727.

CERP (Comprehensive Everglades Restoration Plan). 2013. Central and Southern Florida project. Project Management Plan Indian River Lagoon-South. Army Corps of Engineers, SFWMD (South Florida Water Management District).

Clements R, Rogers AJ. 1964. Studies of impounding for the control of salt marsh mosquitoes in Florida, 1958–1963. Mosq News. 24:265–276.

Donnelly MJ, Shaffer M, Connor S, Sacks P, Walters L. 2017. Using mangroves to stabilize coastal historic sites: deployment success versus natural recruitment. Hydrobiologia. 803(1):389–401.

Donnelly MJ, Walters L, Shaffer M. 2018. Shoreline characterization for northern Indian River Lagoon and Mosquito Lagoon. CEELAB Research Data. Orlando, FL: University of Central Florida. https://stars.library.ucf.edu/ceelab-researchdata/1, accessed March 2022.

FDEP (Florida Department of Environmental Protection). 2009a. Mosquito Lagoon Aquatic Preserve Management Plan. Tallahassee, FL: Florida Department of Environmental Protection. Available from http://publicfiles.dep.state.fl.us/cama/plans/aquatic/Mosquito-Lagoon-AP-Management-Plan-2009.pdf.

FDEP (Florida Department of Environmental Protection). 2009b. TMDL report: nutrient and dissolved oxygen TMDLs for the Indian River Lagoon and Banana River Lagoon. Tallahassee, FL: Florida Department of Environmental Protection. Available from https://floridadep.gov/sites/default/files/indian-banana-nutrient-do-tmdl.pdf.

FDEP (Florida Department of Environmental Protection). 2009c. North Fork St. Lucie River Aquatic Preserve Management Plan. Tallahassee, FL: Florida Department of Environmental Protection. Available from publicfiles.dep.state.fl.us/CAMA/plans/aquatic/North-Fork-St-Lucie-AP-Management-Plan.pdf.

FDEP (Florida Department of Environmental Protection). 2013. Basin management action plan for the implementation of total maximum daily loads for nutrients in the Indian River Lagoon Basin Banana River Lagoon. Tallahassee, FL: Florida Department of Environmental Protection. Available from https://floridadep.gov/sites/default/files/banana-river-lagoon-bmap.pdf.

FDEP (Florida Department of Environmental Protection). 2016. Indian River Lagoon aquatic preserves system management plan. Tallahassee, FL: Florida Department of Environmental Protection. Available from http://publicfiles.dep.state.fl.us/CAMA/plans/aquatic/Indian-River-Lagoon-AP-System-Management-Plan.pdf.

FDEP (Florida Department of Environmental Protection). 2020. 2021 Florida Forever five-year plan Indian River Lagoon blueway summary of recommendations and status as of December 2020. Tallahassee, FL: Florida Department of Environmental Protection. Available from https://floridadep.gov/sites/default/files/FLDEP_DSL_OES_FF_BOT_IndianRiverLagoonBlueway.pdf.

FDOT (Florida Department of Transportation). 1999. Florida land use, cover and forms classification system, 3rd edition. Tallahassee, FL: Florida Department of Transportation, State Topographic Bureau, Thematic Mapping Section. Available from https://www.fdot.gov/docs/default-source/geospatial/documentsandpubs/fluccmanual1999.pdf.

Feller IC, Dangremond EM, Devlin DJ, Lovelock CE, et al. 2015. Nutrient enrichment intensifies hurricane impact in scrub mangrove ecosystems in the Indian River Lagoon, Florida, USA. Ecology. 96(11):2960–2972.

Fillyaw RM, Donnelly, MJ, Litwak JW, Rifenberg JL, Walters LJ. 2021. Strategies for successful mangrove living shoreline stabilizations in shallow water subtropical estuaries. Sustainability. 13(21):11704.

Giri CP, Long J. 2014. Mangrove reemergence in the northernmost range limit of eastern Florida [letter]. PNAS. 111:E1447–E1448.

IRLNEP (Indian River Lagoon National Estuary Program). 2008. Indian River Lagoon comprehensive conservation and management plan update. Palm Bay, FL: Indian River Lagoon National Estuary Program. Available from https://www.epa.gov/sites/production/files/2015-09/documents/ccmp_update_2008_final.pdf.

IRLNEP (Indian River Lagoon National Estuary Program). 2019. Looking ahead to 2030: a 10-year comprehensive conservation and management plan for the Indian River Lagoon, Florida. Palm Bay, FL: Indian River Lagoon National Estuary Program. https://onelagoon.org/management-plan/, accessed February 2022.

Kennedy JP, Preziosi RF, Rowntree JK, Feller IC. 2020. Is the central-marginal hypothesis a general rule? Evidence from three distributions of an expanding mangrove species, *Avicennia germinans* (L.) L. Mol Ecol. 29(4):704–719.

Kibler KM, Donnelly M, Cannon D, Phagan J, et al. 2020. Developing a shoreline restoration suitability model for North Indian River and Mosquito Lagoon, Phase II. Orlando, FL: University of Central Florida. Indian River Lagoon National Estuaries Program Report IRL2018-017. Available from https://stars.library.ucf.edu/cgi/viewcontent.cgi?article=1000&context=shorelines.

Kottek M, Grieser J, Beck C, Rudolf B, Rube F. 2006. World map of the Köppen-Geiger climate classification updated. Meteorol Z. 15(3):259–263.

Lewis FG III. 1984. Distribution of macrobenthic crustaceans associated with *Thalassia, Halodule* and bare sand substrata. Mar Ecol Prog Ser. 19:101–113.

Lewis RR, Gilmore RG Jr, Crewz DW, Odum WE. 1985. Mangrove habitat and fishery resources of Florida. In: Seaman W Jr, editor. Florida aquatic habitat and fishery resources. Kissimmee, FL: American Fisheries Society, Florida Chapter. p. 281–336.

Loch JM, Walters LJ, Donnelly MJ, Cook GS. 2021. Restored coastal habitat can "reel in" juvenile sportfish: population and community responses in the Indian River Lagoon, Florida, USA. Sustainability. 13(22):12832.

Lovelock CE, Ball MC, Martin KC, Feller IC. 2009. Nutrient enrichment increases mortality of mangroves. PLoS One. 4(5):e5600.

Mason WT Jr, Mattson RA, Epler JH. 1994. Benthic invertebrates and allied macrofauna in the Suwannee River and estuary ecosystem, Florida. Fl Sci. 57:141–160.

McClenachan G, Witt M, Walters LJ. 2021. Replacement of oyster reefs by mangroves: unexpected climate-driven ecosystem shifts. Glob Change Biol. 27(6):1226–1238.

McRae G, Madley K. 2001. Florida's inshore marine monitoring and assessment program (IMAP) annual report, year two. St Petersburg, FL: Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute. Available from https://f50006a.eos-intl.net/F50006A/OPAC/Common/Pages/GetDoc.spx?ClientID=MF50006A&MediaCode=5606467.

Mermillod-Blondin F, Rosenberg R, Francois-Carcaillet F, Norling K, Mauclaire L. 2004. Influence of bioturbation by three benthic infaunal species on microbial communities and biogeochemical processes in marine sediment. Aquat Microb Ecol. 36:271–284.

Morris LJ, Hall LM, Jacoby CA, Chamberlain RH, et al. 2022. Seagrass in a changing estuary, the Indian River Lagoon, Florida, United States. Front Mar Sci. https://doi.org/10.3389/fmars.2021.789818

Nicholls RJ, Cazenave A. 2010. Sea-level rise and its impact on coastal zones. Science. 328(5985):1517–1520.

RECOVER (Restoration Coordination and Verification). 2020a. Northern estuaries performance measure: salinity envelope. Jacksonville, FL: U.S. Army Corps of Engineers, Jacksonville District. West Palm Beach, FL: South Florida Water Management District. Available from https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll7/id/14793.

RECOVER (Restoration Coordination and Verification). 2020b. The RECOVER Team's recommendations for revisions to the interim goals and interim targets for the Comprehensive Everglades Restoration Plan: 2020. Jacksonville, FL: U.S. Army Corps of Engineers, Jacksonville District. West Palm Beach, FL: South Florida Water Management District. Available from https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll7/id/14710.

Rey JR, Carlson DB, Brockmeyer RE. 2012. Coastal wetland management in Florida: environmental concerns and human health. Wetl Ecol Manag. 20:197–211.

Rey JR, Shaffer J, Tremain D, Crossman RA, Kain T. 1990. Effects of re-establishing tidal connections in two impounded tropical marshes on fishes and physical conditions. Wetlands. 10:27–47.

Rifenberg J, Litwak J, Fillyaw R. 2021. Vertebrate impact on a newly deployed shoreline stabilization project by wildlife camera analysis. Orlando, FL: The Pegasus Review - University of Central Florida Undergraduate Research Journal. 13(2):3. Available from https://stars.library.ucf.edu/cgi/viewcontent.cgi?article=1136&context=urj.

Rogers K. 2021. Accommodation space as a framework for assessing the response of mangroves to relative sea-level rise. Singap J Trop Geogr. 42(2):163–183.

Rysgaard S, Christensen PB, Nielsen LP. 1995. Seasonal variation in nitrification and denitrification in estuarine sediment colonized by benthic microalgae and bioturbating infauna. Mar Ecol Prog Ser. 126:111–121.

Seitz RD, Lipcius RN, Hines AH, Eggleston DB. 2001. Density-dependent predation, habitat variation, and the persistence of marine bivalve prey. Ecology. 82:2435–2451.

SFWMD (South Florida Water Management District). 2009a. St. Lucie River Watershed protection plan. West Palm Beach, FL: South Florida Water Management District. Available from https://www.sfwmd.gov/sites/default/files/documents/ne_slrwpp_main_123108.pdf.

SFWMD (South Florida Water Management District). 2009b. 2009 SFWMD photointerpretation key. West Palm Beach, FL: South Florida Water Management District. Available from https://www.sfwmd.gov/sites/default/files/documents/2009_pi-key.pdf.

SFWMD (South Florida Water Management District). 2015. North Fork St. Lucie River Floodplain vegetation technical report. West Palm Beach, FL: South Florida Water Management District, Coastal Ecosystems Section. WR-2015-005. Available from http://www.conservationallianceslc.org/uploads/5/0/3/6/50361177/north_fork_sle_vegetation_072115.pdf.

SFWMD (South Florida Water Management District). 2019. SFWMD land cover land use 2017–2019. West Palm Beach, FL: South Florida Water Management District. https://geo-sfwmd.hub.arcgis.com/, accessed July 2022.

Simpson LT, Osborne TZ, Duckett LJ, Feller IC. 2017. Carbon storages along a climate induced coastal wetland gradient. Wetlands. 37(6):1023–1035.

Simpson LT, Osborne TZ, Feller IC. 2019. Wetland soil CO2 efflux along a latitudinal gradient of spatial and temporal complexity. Estuaries Coast. 42(1):45–54.

SJRWMD (St. Johns River Water Management District), Bethune-Cookman University, Florida Atlantic University-Harbor Branch Oceanographic Institution, Florida Fish and Wildlife Conservation Commission, et al. 2012. Indian River Lagoon 2011 superbloom plan of investigation. Palatka, FL: St. Johns River Water Management District. Available from https://www.sjrwmd.com/static/waterways/irl-technical/2011superbloom_investigationplan_June_2012.pdf.

SJRWMD (St. Johns River Water Management District). 2019. St. Johns River Water Management District (SJRWMD) Geospatial Open Data LCLU 2014. Palatka, FL: St. Johns River Water Management District. https://data-floridaswater.opendata.arcgis.com/datasets/floridaswater::opendata-lclu2014/about, accessed February 2022.

SJRWMD (St. Johns River Water Management District). 2018. 2014 land cover update photointerpretation key. Revised March 2018. Palatka, FL: St. Johns River Water Management District. https://www.arcgis.com/home/item.html?id=7fbe3643d8cb45d2868953ee622d834a, accessed February 2022.

SJRWMD (St. Johns River Water Management District) and SFWMD (South Florida Water Management District). 2002. Indian River Lagoon surface water improvement and management plan. Palatka, FL: St. Johns River Water Management District. West Palm Beach, FL: South Florida Water Management District. Available from https://www.researchgate.net/publication/266374140_Indian_River_Lagoon_Surface_Water_Improvement_and_Management_SWIM_Plan_2002_Update.

Smith RS, Osborne TZ, Feller IC, Byers JE. 2019. Detrital traits affect substitutability of a range-expanding foundation species across latitude. Oikos. 128(9):1367–1380.

Swain HM, Breininger DR, Busby DS, Clark KB, et al. 1995. Introduction to the Indian River Biodiversity Conference. Bull Mar Sci. 57:1–7.

Sweat LH, Stephens M, Reed SA. 2021. Insights from 15 years of benthic infaunal monitoring in a coastal lagoon system. Fl Sci. 84:147–161.

Taylor DD. 2012. Removing the sands (sins?) of our past: dredge spoil removal and saltmarsh restoration along the Indian River Lagoon, Florida (USA). Wetl Ecol Manag. 20:213–218.

Tenore KR, Zajac RN, Terwin J, Andrade F, et al. 2006. Characterizing the role benthos plays in large coastal seas and estuaries: a modular approach. J Exp Mar Biol Ecol. 330:392–402.

U.S. Census. 2022. United States Census Bureau state & county quick facts. https://www.census.gov/quickfacts/fact/table/US/PST045221, accessed January 2022.

Virnstein R. 1977. The importance of predation by crabs and fishes on benthic infauna in Chesapeake Bay. Ecology. 58:1199–1217.

Walton AS, Nelson JL, Nappi CJ, Duffey RM, Rasnake EC. 2013. Description of the benthic macroinvertebrate communities of four tidal creeks along the eastern shore of Charlotte Harbor. Fl Sci. 76:121–137.

Word JQ. 1979. The infaunal trophic index. In: Bascom W, editor. Southern California Coastal Water Research Project 1978 annual report. El Segundo, CA: Southern California Coastal Water Research Project. p. 19–39. Available from https://ftp.sccwrp.org/pub/download/DOCUMENTS/AnnualReports/1978AnnualReport/ar01.pdf.

General references and additional regional information

SJRWMD coastal wetlands restoration https://www.sjrwmd.com/education/wetlands/coastal-restoration/

Comprehensive Everglades Restoration Plan (CERP) https://www.evergladesrestoration.gov/comprehensive-everglades-restoration-plan

Indian River Lagoon Species Inventory https://irlspecies.org

Regional contacts

Ron Brockmeyer, St. Johns River Water Management District, rbrockmeyer@sjrwmd.com

Melinda Donnelly, University of Central Florida, melinda.donnelly@ucf.edu

Julie Mitchell, Florida Fish and Wildlife Conservation Commission, julie.mitchell@myfwc.com

Loraé Simpson, Florida Oceanographic Society, lsimpson@floridaocean.org

Holly Sweat, Smithsonian Marine Station, sweatl@si.edu