Chapter 1
Introduction

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Coastal wetland ecosystems of Florida

Mangrove and salt marsh ecosystems occupy the intertidal zones along the coast of Florida. Salt marshes dominate the coast in northern Florida where temperatures occasionally dip below freezing, while mangroves are predominant in the warmer, southern regions. In much of Florida, the ranges of mangroves and salt marshes overlap, and salt marshes often occur landward of a mangrove fringe (Figure 1.1).

Salt marsh vegetation

Salt marshes, also known as tidal or saltwater marshes, occur along the coastal areas of Florida in regions that are protected from large waves by barrier islands, river mouths, or sloping topography and shallow coastal waters (Wiegert and Freeman 1990). The emergent vegetation in salt marshes is predominantly composed of salt-tolerant grasses, rushes, succulents, and shrubs. Marsh profiles and dominant vegetation vary with climate, wave energy, tidal amplitude, geology, and coastal elevation. A marsh is generally separated into two distinct regions, low marsh and high marsh, based upon frequency of tidal flooding and dominant vegetation. The low marsh is flooded during the daily tidal cycle, while the high marsh is flooded only occasionally, during extremely high tides (Wiegert and Freeman 1990).

Juncus roemerianus (black needlerush) and *Spartina alterniflora* (smooth cordgrass) are the most common plants in Florida salt marshes. *J. roemerianus* and *S. alterniflora* typically grow in monotypic bands with abrupt transitions; *S. alterniflora* is more tolerant of flooding and dominates the low marsh, while *J. roemerianus* tolerates a wider range in soil salinity and dominates the high marsh (Stout 1984, Montague and Wiegert 1990). *S. alterniflora* stands range widely in both height and primary productivity. Shoots are frequently less than 1.6 ft (0.5 m) tall, although along banks of tidal creeks shoots may reach heights of 5–10 ft (1.5–3 m) (Weigart and Freeman 1990). *J. roemerianus* is generally found in the more landward high marsh, but may also be found in tidal creeks and in patches amid *S. alterniflora* on mounds with slightly higher elevation.

Other salt-tolerant plants in salt marshes include *Distichlis spicata* (saltgrass), *Monanthochloe littoralis* (key grass), *Spartina spartinae* (Gulf cordgrass), *Batis maritima* (saltwort), *Sesuvium portulacastrum* (sea purslane) and *Salicornia* spp. (glassworts). For detailed species lists, see Montague and Wiegert 1990 and USFWS 1999. Mangroves may also mix with *J. roemerianus* and *S. alterniflora* (Figures 1.2 and 1.3), especially at the salt marsh–mangrove transition. The high marsh is occupied by a more diverse array of plant species, and inland species of plants may be found intruding onto its landward edge and in regions of slightly higher elevation. The oligohaline marsh, with its low salinity of 0.5–5, is also habitat for vegetation with a lower salinity tolerance.

Figure 1.1. Extent of salt marsh and mangrove habitat within Florida.

Salt barrens (also known as salt pans, salt flats, or salterns) are unvegetated, exposed flats with high soil salinity as a result of salt left behind by evaporated seawater. Similarly, salt marsh algae beds are salt barrens dominated by algae rather than vascular plants. Although they lack the emergent vegetation characteristic of coastal wetlands, salt barrens are often classified as a subcategory of salt marshes within land cover classification schemes or simply included as part of the salt marsh mosaic.

Mangrove vegetation

Florida mangrove communities are composed of three mangrove species, *Rhizophora mangle* (red mangrove), *Avicennia germinans* (black mangrove), and *Laguncularia racemosa* (white mangrove). The closely associated *Conocarpus erectus* (buttonwood tree) is also common in Florida mangrove forests. Mangroves are facultative halophytes, meaning they grow well in brackish and salt water but do not require it for survival (Krauss et

Figure 1.2. An abrupt transition from *Juncus roemerianus* salt marsh to mangroves.

Figure 1.3. Low tide in a low marsh dominated by *Spartina alterniflora* and juvenile mangroves.

Figure 1.4. The prop roots of *Rhizophora mangle* stabilize the tree and provide large surfaces for aeration.

Figure 1.5. The pneumatophore roots of *Avicennia germinans* facilitate oxygen uptake.

al. 2008). Rates of mangrove growth and propagule establishment are highest in low to moderate salinities (Ball et al. 1997, Krauss et al. 2008). The mangroves' adaptations that allow them to cope with frequently inundated soil that is both anaerobic and high in salinity enables them to outcompete other plant species in coastal regions. The shade cast by these tall trees also enables them to outcompete other salt-tolerant species.

Rhizophora mangle grows closest to the water's edge. The large prop roots that extend from its trunk and lower branches (Figure 1.4) stabilize the tree and allow the roots to take in oxygen directly from the air rather than from the coastal soil, which is frequently anaerobic (Scholander et al. 1955, Odum and McIvor 1990). *R. mangle* is a salt excluder; the trees avoid taking up salt via a reverse osmosis process (Scholander 1968, Scott 2004) or by taking up freshwater directly when it is available (Kathiresan and Bingham 2001). *C. erectus, L. racemosa,* and *A. germinans* are all salt excreters and expel salt through glands in their leaves and petioles.

Figure 1.6. Leaf examples of *Rhizophora mangle* (left), *Avicennia germinans* (center), and *Laguncularia racemosa* (right). Upper surfaces of leaves are shown in the top row; lower surfaces are in the bottom row.

Figure 1.7. Excreted salt accumulates on the surface of *Avicennia germinans* leaves.

Avicennia germinans generally grows intermixed with or landward of *R. mangle*. They have an extensive network of cable roots and vertical root projections known as pneumatophores (Figure 1.5) that provide stability and aeration for the trees (Scholander et al. 1955, Scott 2004). The leaves (Figures 1.6 and 1.7), often encrusted in salt, are a shiny green and have small hairs on the lighter-colored underside. *A. germinans* is the most cold tolerant of the Florida mangrove species and can sprout from its root system after cold-induced dieback (Odum and McIvor 1990).

Laguncularia racemosa is generally found intermixed with or at higher elevations than *A. germinans*. *L. racemosa* can occasionally develop vertical roots including pneumatophores or pneumathodes, a slender vertical root that lacks an epidermis (Geissler et al. 2002, Nelson 2011). Also a salt excreter, *L. racemosa* has more oval leaves than the other mangrove species, and extrafloral nectaries on the petiole are visible as small protuberances (Figure 1.6).

Mangrove development is a viviparous process because the embryo germinates and grows as a propagule while still attached to the parent tree. The propagules are dispersed by water currents and can establish quickly in new areas through rapid root growth.

Conocarpus erectus (buttonwood tree) grows on the landward edge of mangrove swamps. The buttonwood tree gets its name from its small green spherical flowers. While not a true mangrove, *C. erectus* is a member of the family Combretaceae along with *L. racemosa (*Nelson 2011). *C. erectus* is salt tolerant, but it does not have a specialized root system or propagules (Odum et al. 1982, Nelson 2011).

Salt marsh and mangrove communities are often in flux with one another (Montague and Odum 1997). Mangrove communities often overtake salt marsh habitat (Figure 1.3), as the herbaceous marsh vegetation cannot survive in the shade of the mangrove trees. Occasional cold events, however, can cause extensive mangrove die-offs, after which salt marsh plants rapidly replace the mangrove swamps. The marsh may once again return to a mangrove-dominated ecosystem after the trees grow back from root stock or the establishment and growth of new mangrove propagules.

Ecological and economic value of salt marsh and mangrove ecosystems

Both mangrove swamps and salt marshes provide ecological and economic value through their ability to stabilize shorelines, support coastal fisheries, sequester carbon, and filter nutrients and other pollutants from runoff (Thayer et al. 1987, Kathiresan and Bingham 2001). The value of the ecosystem services provided by coastal wetlands has been placed at $10,000 per hectare (Barbier et al. 2011, Kirwan and Megonical 2013). Economic value varies widely by location and study, as storm surge protection and surface water treatment may be assessed at a higher value when adjacent to coastal development.

Salt marshes have one of the highest rates of primary production among the world's ecosystems (Montague and Wiegert 1990). Atmospheric carbon is sequestered in plant biomass and buried as peat in both salt marsh and mangrove ecosystems (Table 1.1) (Kathiresan and Bingham 2001, Russell and Greening 2015). Carbon that

Table 1.1. Estimated rates of carbon sequestration and denitrification (mean ± standard error) in selected ecosystems (table adapted from Bowden 1986, Mcleod et al. 2011, and Russel and Greening 2015).

Habitat	Carbon sequestration rate ($gC/m^2/yr$)	Denitrification rate ($gN/m^2/yr$)
Mangrove	226 ± 39	4 ± 2.0
Salt marsh	218 ± 24	1 ± 0.1
Seagrass	138 ± 38	9 ± 2.2
Temperate forest	5.1 ± 1.0	0.1–1
Tropical forest	4.0 ± 0.5	0.3
Boreal forest	4.6 ± 2.1	trace

is captured and sequestered by coastal wetlands and seagrass beds, known as blue carbon, acts as a sink in the global carbon cycle (Cebrian 2002, Kathiresan 2012). Loss of coastal wetlands across the planet may therefore have a significant impact on the global carbon budget. Likewise, the carbon sequestration that takes place as a result of coastal wetland restoration projects can now earn carbon credits for greenhouse gas reductions (VCS 2015).

Coastal wetlands play an important ecological role in the breakdown and biogeochemical cycling of organic matter, nutrients, and even some pollutants. The grasses in salt marshes slow the passage of water, enabling sediment deposition and facilitating nutrient uptake (Hammer 1989, Kathiresan and Bingham 2001, Barbier et al. 2011). Nutrients are not only taken up by plants and algae, but nitrate and nitrite are also converted to atmospheric nitrogen by denitrifying bacteria (Table 1.1). Water that has run through coastal wetlands has a lower nutrient concentration, reducing the need for artificial stormwater treatment (Russel and Greening 2015). Wetlands can also remove low amounts of water pollutants and metals such as iron, copper, and manganese through adsorption to fine-grained sediments and subsequent deposition (Lee et al. 2006). If the sediment is later disturbed, however, these pollutants are again released to the water column (Dyer 1995). While sediments in mangrove swamps can have high concentrations of heavy metals, the mangrove trees themselves maintain a low heavy metal concentration (Kathiresan and Bingham 2001).

Because they are situated on coastal boundaries, mangroves and salt marshes provide essential ecological services to both terrestrial and marine species. The dense vegetation provides a complex habitat that is used as a nursery shelter by many ecologically and commercially important fish and invertebrate species, such as *Centropomus undecimalis* (common snook), *Megalops atlanticus* (tarpon), *Crassostrea virginica* (eastern oyster), *Callinectes sapidus* (blue crab), and coastal shrimp (Lewis et al. 1985, Wiegert and Freeman 1990, Barbier et al. 2011). Both local and migratory birds use salt marshes as feeding and nesting grounds. *Mycteria americana* (Wood Stork), *Platalea ajaja* (Roseate Spoonbill), *Pandion haliaetus* (Osprey), *Tringa semipalmata* (Eastern Willet), and multiple species of herons and egrets use coastal wetlands for foraging or roosting. Salt-tolerant reptiles also use the lush habitat; *Malaclemys terrapin* (diamondback terrapin) and some subspecies of *Nerodia fasciata* (salt marsh snake) reside exclusively in salt marshes and mangroves (Montague and Wiegert 1990).

Salt marshes and mangroves stabilize shorelines, protecting inland ecosystems and human developments from wave energy, storm surge, and erosion (Barbier et al. 2011). While the shorelines of salt marshes are often eroded during large storms, the eroded sediment may be returned to the marshes during calmer intervals (Pethick 1992, Boorman 1999). The dynamic capacity to erode and redeposit sediment can make salt marshes more valuable than sea walls for protecting inland property, but marshes must be sufficiently broad in order to be a resilient storm buffer (King and Lester 1995, Boorman 1999). Mangroves also stabilize shorelines and reduce the wave and wind energy from tropical storms, providing some protection to inland developments (Kathiresan 2012, McIvor et al. 2012).

Common threats to Florida's coastal wetlands

Habitat loss

In the early 1800s Florida had an estimated 20.3 million acres (8.2 million ha) of freshwater and coastal wetlands (Dahl 2005). In the past one hundred years, high rates of coastal development in Florida have been detrimental to both habitat extent and health of coastal ecosystems. Coastal wetlands have been destroyed directly due to residential and commercial development and indirectly by pollution and changes in hydrology. Hefner (1986) estimated that from the mid-1950s to the mid-1970s, before wetlands were protected, 72,000 acres (29,137 ha) of wetlands were lost each year. By the 1980s, an estimated 23% (150,000 acres/60,702 ha) of historical mangrove coverage had been lost to development (Lewis et al. 1985). Governmental regulations such as the Clean Water Act in 1972 helped slow the filling of coastal wetlands (Dahl 2011). From 1985 to 1996, this annual rate of loss decreased to 5,000 acres (2,023 ha) due to the protection efforts of federal, state, and local governments and nongovernmental organizations (Dahl 2005).

Figure 1.8. Dead mangroves at the proposed Fruit Farm Creek mangrove restoration area within the Rookery Bay National Estuarine Research Reserve, Naples, Florida. Photograph by Cynthia Sapp.

Altered hydrology

Hydrology has been drastically altered across Florida by road construction, flood control structures, urban and agricultural water usage, mosquito ditching, and shoreline hardening. Impermeable surfaces and drainage systems concentrate terrestrial runoff, decreasing salinity in many coastal wetlands while concentrating freshwater outflow near culverts and streams (Lee et al. 2006). Seawalls, breakwaters, impoundments and other constructed features also alter hydrologic flow and can cause coastlines to be starved of or inundated by sediment (Bulleri and Chapman 2010). In some regions, blocked tidal flows and resulting stagnant water can slowly kill mangroves, resulting in localized die-offs (Figure 1.8). A lack of flushing can cause stress in the form of stagnation, anoxia, or hypersalinity. Stressed vegetation is more vulnerable to secondary stressors such as fungal infections and excessive herbivory (Silliman et al. 2005, Elmer et al. 2012).

From the 1930s to the 1960s, an extensive array of mosquito ditches was dug to drain marshes in an effort to reduce the *Aedes* spp. (marsh mosquito) population (Montague and Wiegert 1990). In the 1940s, salt marshes were also sprayed with DDT, which decreased the mosquito population until DDT-resistant strains of mosquitoes developed. Salt marshes were also impounded and flooded for mosquito control, as *Aedes* spp. will not lay eggs on standing water. These marsh impoundments altered natural water levels and restricted tidal flow, resulting in the decline of native flora and fauna and the incursion of freshwater species such as *Typha* spp. (cattails) and various species of invasive submerged aquatic vegetation. Impounded marshlands did, however, prove beneficial for some Florida species, particularly wading birds.

Climate change and sea-level rise

Dahl (2011) estimated that 99% of coastal wetland losses from 2004 through 2009 in the contiguous United States were due to saltwater intrusion, storms, land subsidence, sea-level rise, and associated erosion and marine processes. Sea level has crept up at a rate of 2–3 mm/yr over the past 50 years for most locations in Florida (NOAA 2014). Sea-level rise has large implications for salt marshes and mangrove communities as the vegetative community is affected primarily by frequency of tide inundation and salinity (Stout 1984).

Coastal wetlands can accommodate a certain extent of sea-level rise as they accumulate peat and trap sediment washed in by tides or storms. If these feedback mechanisms of vertical substrate accretion, subsurface expansion, and plant growth rate manage to keep up with sea-level rise, they may allow coastal wetlands to maintain their current position (Kirwan and Megonigal 2013). But sea-level rise and the concurrent increase in the salinity of pore water will likely accelerate the decomposition of soil organic matter in regions previously exposed to low salinity. Seawater provides sulfate, which microbes can use as a terminal electron acceptor for the remineralization of organic matter, enabling decomposition in anaerobic environments (Snedaker 1993). Landward salt marsh migration is possible where natural buffer zones of appropriate elevation are present, yet this may be hindered by local topography, urban development, or hardened shorelines such as seawalls or riprap (Montague and Wiegert 1990).

Inland migration of mangrove communities often results in mangroves encroaching on and overtaking salt marsh habitat (Saintilan et al. 2009, Krauss et al. 2011). The extent of mangrove communities increased 35% from 1927 to 2005 in the Ten Thousand Islands National Wildlife Refuge as mangroves overtook adjacent inland habitats (Krauss et al. 2011). This mangrove expansion is attributed to a combination of sea-level rise, altered hydrology, and other interacting factors (Krauss et al. 2011).

Mangroves have expanded their range both landward and northward in Florida (Williams et al. 2014). *A. germinans* expansion northward has been linked to a recent decrease in the frequency of cold events in central to northern Florida (Stevens et al. 2006). Cavanaugh et al. (2014) found a strong correlation between the increase in mangrove cover and the decrease in the number of days on which the temperature fell below −4°C. Mangrove extent north of 27°N latitude has increased in recent decades on the eastern coast of Florida; in some areas the extent of mangroves doubled from 1985 to 2011 (Cavanaugh et al. 2014). Portions of this recent mangrove expansion can be attributed to recovery from cold-event mortalities from the 1960s through the 1980s (Giri and Long 2014). In their northward migration, mangroves encroach on and replace salt marsh habitat. Given continued warming trends, mangroves may overtake salt marsh ecosystems for significant portions of the coast along northeastern Florida and the Gulf of Mexico (Osland et al. 2013). While mangroves support an important and productive ecosystem, local and migratory birds that use salt marshes as foraging and breeding grounds may be disadvantaged by this loss of habitat (Krauss et al. 2011).

Poor water quality

Runoff from urban and agricultural areas brings nutrients, pesticides, herbicides, hydrocarbons, and heavy metals into coastal wetlands (Kathiresan and Bingham 2001, Lee et al. 2006). Salt marshes have also been used directly as dumps for industrial and household pollutants and sewage (Montague and Wiegert 1990, Lee et al. 2006). While wetlands can absorb and utilize nutrients in runoff to a certain extent, high nutrient concentrations can cause eutrophication, hypoxia from the resulting algal blooms, and declines in species diversity (Lee et al. 2006).

Invasive species

Invasive species such as *Schinus terebinthifolius* (Brazilian pepper), *Melaleuca quinquenevria* (melaleuca), and *Casuarina* spp. (Australian pines) are maintaining a persistent presence on the borders of coastal wetland habitat in Florida. Rapid growth of these invasive species often outpaces growth by native marsh plants, particularly after a disturbance such as a hurricane or construction (USFWS 1999). *S. terebinthifolius* can easily take over a region after disturbances and produces chemicals that impede the growth of other plants. *M. quinquenevria* can invade pristine ecosystems; its roots then alter hydrologic patterns by absorbing large amounts of water, effectively excluding other plants. As a tall, salt-tolerant tree, *Casuarina* spp. easily shades out and displaces other species and a dense layer of its needlelike leaves accumulates under the trees, hindering the growth of native seedlings (Batish and Singh 1998).

Illegal trimming of mangroves

While a more minor concern than the previously mentioned threats to coastal wetlands, mangrove trimming practices for waterfront views often do not adhere to the 1996 Mangrove Trimming and Preservation Act. Common improper trimming includes severe hedging, in which the canopy of the mangroves is cut back to form a low hedge with unobstructed waterfront view. Hedging can meet trimming guidelines so long as the upper canopy is preserved, generally leaving at least 6 feet of height (1.83 m). Detailed mangrove trimming guidelines for homeowners are available from the Florida Department of Environmental Protection at www.dep.state.fl.us/water/wetlands/mangroves/docs/Mangrove-Homeowner-Guide.pdf.

Classification of coastal wetlands by remote-sensing techniques

Several techniques are used to categorize land cover and determine the spatial extent of coastal wetlands. Data sources include aerial photography and videography, high- and medium-resolution satellite images, hyperspectral sensors, radar, and LiDAR (Light Detection And Ranging), all of which provide data of variable utility, detail, and cost (Kuenzer et al. 2011). Visual elements of remote sensing images, such as color, gray tones, shadows, texture, and proximal associations, can be used to determine land use and wetland extent (Lyon 2001). Remote sensing of near-infrared light can be used to determine the health of plants. Live plants reflect infrared light; this reflected light is frequently visualized using a red color on aerial images. Healthy plants therefore appear bright pink or magenta, while unhealthy or dead plants appear darker (Lyon 2001, Kuenzer et al. 2011). The normalized difference vegetation index (NDVI) is calculated using visible and near-infrared light to assess vegetative ground cover or biomass. Near-infrared wavelengths are also useful for locating the waterline, as even a small amount of water will absorb infrared light (Lyon 2001).

Remote sensing of coastal wetlands is complicated by the variety of substrates and vegetation that make up these habitats. Leaves, branches, soil, and water are all parts of mangrove ecosystems, yet each has a unique spectral signature. Each mangrove species has unique spectral characteristics; even within a single species the spectral signature can vary with physiology, vitality, age, and season (Blasco et al. 1998, Wang et al. 2008, Kuenzer et al. 2011). Categorization is further complicated by the patchiness of mangrove ecosystems and intermingling with other types of vegetation. Intermittent patches of mangroves can be misclassified as mud flats or residential areas. Widely variable water levels in coastal wetlands due to tidal fluctuation, drought, or floods also make it difficult to discern if differing appearances are due to a change in land use or water level (Gao 1998). Precipitation also affects the appearance of waterways; clear, shallow water may appear dark or reflective, yet after rain the same waterway may be opaque due to suspended sediments (Lyon 2001).

Aerial photography and videography

Aerial photographs provide excellent spatial resolution at relatively low cost. They are extremely useful for local projects or for the creation of highly detailed maps, particularly where wetland extent is narrow or patchy. The availability of historical photographs makes aerial photography a useful tool for the study of changes in land use. Care must be taken, however, because image appearance can vary daily with cloud cover and shadow extent. Seasonal changes and precipitation alter foliage density and color, so it is optimal to compare land-use changes using photos taken at the same time of day and in the same season (Lyon 2001).

Satellite imagery

The use of aerial photography for land use mapping has somewhat declined with the advent of satellite imagery (Kuenzer et al. 2011). Costs increase with spatial coverage, so satellite data are more cost-effective for large-scale projects. Temporal variability in images due to calibration drift or variable sun angle and weather can be smoothed by image preprocessing and compiling images from multiple dates (Lyon 2001). Medium-resolution imagery is useful for general land use mapping and change detection on a large scale, but the spatial and temporal resolution may be too coarse to reveal details such as mangrove species or damage immediately following a hurricane or other extreme event. The medium-resolution images used for mangrove mapping commonly come from the Landsat (land remote-sensing satellite) series (Kuenzer et al. 2011). High-resolution imagery provides greater detail (resolution of 1.6–13 ft/0.5–4 m) than medium-resolution imagery but is more expensive.

Active remote sensing

In active remote sensing, terrestrial features are mapped by measuring the time it takes a pulse of a given wavelength to bounce off of a target and return to the sensor. LiDAR uses visible wavelengths, whereas radar uses microwaves. Unlike passive sensors that depend upon visible light, active radar sensors can be used in cloudy weather and at night (Kuenzer et al. 2011). Because the rapid laser pulses can penetrate gaps in tree canopy and reach the ground, LiDAR is useful for determining tree height and topography beneath mangroves. This technique is less useful in salt marshes as the dense cover of vegetation prevents the laser pulses from reaching the ground (Medeiros et al. 2015).

Image categorization of land use

Land cover categorization is initialized with either unsupervised or supervised classification of a training data set. In supervised classification, a researcher uses a data set of locations with known land cover to determine the spectral signatures of each land cover type. In unsupervised training, a computer algorithm clusters data based upon similar spectral characteristics (Lyon 2001, McCarthy et al. 2015). The accuracy of these preliminary clusters to classify land cover types is then assessed with ground truthing or aerial photographs. Clusters of similar land cover may be merged and the classification system is edited as needed (Gao 1998, Lyon 2001, Kuenzer et al. 2011).

Several methods can be used to analyze change in land use (Lyon 2001). Before categorization, aerial photographs may be transformed into single or multiband images through image enhancement in order to facilitate change detection. Alternatively, a principal components analysis may be used to compress variability from multiple spectral bands into a few principal components (Lyon 2001). In postcategorization methods, two images are categorized into their respective land cover types independently. The resulting land cover maps are then compared to each other to discern changes in land use.

Land cover classification schemes

A variety of land cover classification schemes exists both nationally and within Florida. Some of these classification schemes place greater emphasis on human development, while others focus on vegetation and ecosystem characteristics. Many of these schemes are hierarchical and become more specific at each higher level of classification. Selected statewide and national classification schemes are summarized in Table 1.2 and described in further detail below. In general *C. erectus* is either included as part of a mangrove swamp classification or, in some cases, as a subcategory of mangrove swamps (FNAI 2010). Similarly, salt barrens are included as part of salt marshes, while the Florida Natural Areas Inventory (FNAI) organizes salt barrens as a subcategory of salt marshes (FNAI 2010). Classification schemes may further subdivide mangrove and salt marsh habitats based on plant species composition (FDOT 1999, Kawula 2009, FNAI 2010), mangrove height (Cowardin et al. 1979), and general ecotype regions in Florida (NatureServe 2007). Some classification schemes also include a separate category for scrub mangrove ecosystems in the Florida Keys (Gilbert and Stys 2004, Kawula 2009, FNAI 2010).

Florida land cover classification schemes

The Florida Land Use and Cover Classification System (FLUCCS) was created by the surveying and mapping office of the Florida Department of Transportation (FDOT). The original classifications were published in 1985 (FDOT 1985) and the current wetland categories added in the 1999 revision (FDOT 1999). Florida water management districts (WMDs) use FLUCCS for land classifications and may modify them for their district (SFWMD 2009, SJRWMD 2009). Relevant FLUCCS classifications and their corresponding numbers include the following.

6000 Wetlands: water table meets or exceeds land height for a significant portion of the year
- **6100 Wetland hardwood forests:** 66% or more dominated by wetland hardwood species; freshwater or saltwater
  - **6120 Mangrove swamps:** dominated by mangrove trees, also may include buttonwood, cabbage palm, and sea grape
- **6400 Vegetated nonforested wetlands:** includes freshwater and saltwater marshes
  - **6420 Saltwater marshes:** dominated by specific salt-tolerant vegetation
    - **6421 Cordgrass:** 66% or more of vegetative cover is *Spartina* spp.
    - **6422 Needlerush:** 66% or more of vegetative cover is *J. roemerianus*

The Guide to the Natural Communities of Florida was first published in 1990 by the Florida Natural Areas Inventory (FNAI 1990). In 2010, the guide was updated to provide additional classifications and further information, such as species data, to aid in distinguishing among similar communities. Relevant FNAI 2010 classifications include the following.

Marine and estuarine vegetated wetlands: intertidal or supratidal wetlands with herbaceous or woody plants and salinity >0.5
- **Salt marsh:** herbaceous plants; few shrubs, no trees
  - **Salt flat:** dry, exposed salt marsh with bare soil and high salinity; sparse vegetation
- **Mangrove swamp:** wetland dominated by mangroves and buttonwood
  - **Buttonwood forest:** dominated by buttonwood trees
- **Keys tidal rock barren:** herbaceous vegetation and stunted trees, located on regions with exposed limestone in the Florida Keys

The Florida Fish and Wildlife Conservation Commission (FWC) created Florida land cover maps using 2003 data from Landsat TM (thematic mapper) satellite imagery (Gilbert and Stys 2004, Stys et al. 2004), updating the FWC land cover maps created using 1985–1989 data (Kautz et al. 1993). The 2003 land cover project used unsupervised classification schemes to categorize land cover. The final products included detailed descriptions of 43 land cover categories, published in Gilbert and Stys (2004). Relevant classifications include the following.

Table 1.2. Selected land cover and vegetation classification schemes.

Name	Affiliation	Region	Coastal Wetland Classification Scheme	Reference

Florida Land Use and Cover Classification System (FLUCCS)	Florida Department of Transportation (FDOT)	Florida	Wetlands
			  Wetland hardwood forests
			    Mangrove swamp
			  Vegetated nonforested wetlands
			    Saltwater marshes
			      Cordgrass
			      Needlerush
				FDOT 1999

Guide to the Natural Communities of Florida	Florida Natural Areas Inventory (FNAI)	Florida	Marine and estuarine vegetated wetlands
			  Salt marsh
			    Salt flat
			  Mangrove swamp
			    Buttonwood forest
			  Keys tidal rock barren
				FNAI 2010

Descriptions of Vegetation and Land Cover Types Mapped Using Landsat Imagery	Florida Fish and Wildlife Conservation Commission (FWC)	Florida	Marine and estuarine
			  Salt marsh
			  Mangrove swamp
			  Scrub mangrove (Keys only)
				Gilbert and Stys 2004

Florida Land Cover Classification System	FWC	Florida	Estuarine, intertidal
			  Exposed limestone
			    Vegetated
			      Keys tidal rock barren
			  Tidal marsh
			    Tidal marsh barren
			    Saltwater marshes
			      Cordgrass
			      Needlerush
			  Tidal swamp
			    Mangrove
				Kawula 2009

Vegetation Classification for South Florida Natural Areas	University of Georgia, U.S. National Park Service, South Florida Water Management District	Everglades	Forest
			  Mangrove forest
			Woodland
			  Mangrove woodland
			Shrubland
			  Mangrove shrubland
			Scrub
			  Mangrove scrub
			Marsh
			  Salt marsh
			(partial list; further subdivisions available)
				Rutchey et al. 2006

NatureServe Terrestrial Ecological Classifications	NatureServe, Landfire, The Nature Conservancy	Southeastern United States	Woody wetlands and riparian
			  Caribbean coastal wetland systems
			    South Florida mangrove swamp
			    Southwest Florida perched barriers tidal swamp and lagoon
			Herbaceous wetlands
			  Gulf and Atlantic coastal plain tidal marsh systems
			    Atlantic coastal plain Indian River Lagoon tidal marsh
			    Central Atlantic coastal plain salt and brackish tidal marsh
			    Florida Big Bend salt and brackish tidal marsh
				NatureServe 2007

Table 1.2 (continued). Selected land cover and vegetation classification schemes.

Name	Affiliation	Region	Coastal Wetland Classification Scheme	Reference
Classification of Wetlands and Deepwater Habitat of the United States	U.S. Fish and Wildlife Service	National	Estuarine, intertidal Emergent wetland Persistent Scrub-shrub wetland Broad-leaved evergreen Forested wetland Broad-leaved evergreen	Cowardin et al. 1979
National Vegetation Classification Standard, v. 2	Federal Geographic Data Committee	National	Forest and woodland Tropical moist forest Mangrove Shrubland and grassland Temperate and boreal shrubland and grassland Temperate and boreal salt marsh (partial list, further subdivisions available)	FGDC 2008
National Land Cover Data (NLCD)	U.S. Geological Survey (USGS)	National	Wetlands Woody wetlands Emergent herbaceous wetlands	www.mrlc.gov Vogelmann et al. 1998
Coastal Change Analysis Program (C-CAP) Classification System	National Oceanic and Atmospheric Administration (NOAA)	National	Wetland Marine/estuarine emergent wetland Haline (salt marsh) Mixohaline (brackish marsh) Estuarine woody wetland Evergreen Forest Scrub–shrub Dead	Klemas et al. 1993, Dobson et al. 1995

Marine and estuarine

- **23. Salt marsh:** herbaceous and shrubby wetland in brackish waters
- **24. Mangrove swamp:** dominated by mangroves and buttonwood trees; transitional regions may include salt marsh species
- **25. Scrub mangrove:** few small mangroves (Florida Keys only)

The Florida Land Cover Classification System (Kawula 2009) was developed to create a single land cover classification scheme for Florida by integrating established classification systems. The Florida Land Cover Classification System's hierarchical classification scheme is based on the FNAI's Guide to the Natural Communities of Florida (FNAI 1990), FWC land cover descriptions (Gilbert and Stys 2004, Stys et al. 2004), FLUCCS classifications (FDOT 1999), and modifications made by various WMDs (Kawula 2009, SFWMD 2009, SJRWMD 2009). Relevant classifications (nonvegetated classifications omitted) include the following.

5000 Estuarine
- **5200 Intertidal**
  - **5210 Exposed limestone**
    - **5211Vegetated**
      - **52111 Keys tidal rock barren:** herbaceous vegetation and stunted trees, located on regions with exposed limestone in the Florida Keys
  - **5240 Tidal marsh:** wetland inundated by tides daily, dominated by herbaceous plants with few shrub
    - **5241 Tidal marsh barren:** exposed, mostly bare dry soil with high salinity
    - **5242 Saltwater marshes:** estuarine wetland dominated by specific salt-tolerant plants
      - **52421 Cordgrass**
      - **52422 Needlerush**
  - **5250 Tidal swamp:** wetland dominated by mangroves or buttonwood
    - **5251 Mangrove:** coastal hardwood community with mangroves, buttonwood, and associated vegetation

The Vegetation Classification for South Florida Natural Areas is a specialized hierarchical classification system designed for the Everglades and surrounding areas (Rutchey et al. 2006). The system was developed to facilitate tracking vegetation changes as a component of the Comprehensive Everglades Restoration Plan (CERP). It was prepared by the U.S. Geological Survey (USGS) in cooperation with several other agencies (Rutchey et al. 2006). Each of the following categories contains numerous species-specific subgroups, including mixtures of multiple vegetation types. The classification system also includes species-specific categories for common invasive vegetation. Relevant classifications include the following.

Forest (F): high-density (>50% tree canopy cover) stands of trees >5 m (16.4 ft) high
- **Mangrove forest (FM):** regularly flooded forests with mangrove or buttonwood

Woodland (W): low-density stands of trees >5 m (16.4 ft) high
- **Mangrove woodland (WM):** regularly flooded woodland with mangroves and buttonwood

Shrubland (S): high-density stands of trees or shrubs <5 m (16.4 ft) high
- **Mangrove shrubland (SM):** regularly flooded shrubland with mangroves

Scrub (C): dwarf trees or low-density shrubs
- **Mangrove scrub (CM):** regularly flooded scrub with mangroves

Marsh (M): graminoid or herbaceous vegetation in shallow water
- **Salt marsh (MS):** salt-tolerant graminoid or herbaceous vegetation

The NatureServe terrestrial ecological classifications were developed specifically for the southeastern United States (NatureServe 2007). These ecological descriptions were prepared by the nonprofit conservation organizations NatureServe (www.natureserve.org) and The Nature Conservancy (www.nature.org) for LANDFIRE (landscape fire and resource management planning tools), a geospatial program that includes databases, ecological models, and land cover data for use in fire and resource management (www.landfire.gov). This classification system is specific not only to vegetation, but also to regional hydrology, geology, and energy input. Relevant NatureServe classifications include the following.

Woody wetlands and riparian
- **1470 Caribbean coastal wetland systems**
  - **South Florida mangrove swamp:** dominated by mangroves and buttonwood. Soils generally saturated at all times with brackish waters and flooded regularly by tides
  - **Southwest Florida perched barriers tidal swamp and lagoon:** includes mangrove forests with canopies up to 10 m (32 ft) tall and salt marshes. Extends from Tampa Bay to Charlotte Harbor. The term perched refers to elevated barrier islands

Herbaceous wetland
- **1490 Gulf and Atlantic coastal plain tidal marsh systems**
  - **Atlantic coastal plain Indian River Lagoon tidal marsh:** primarily high marshes that are protected by barrier islands along the Indian River lagoon
  - **Central Atlantic coastal plain salt and brackish tidal marsh:** dominated by *S. alterniflora* and *J. roemerianus*; occurs in northern Florida on the Atlantic coast. Has different tides and energy than Gulf coast salt marshes
  - **Florida Big Bend salt and brackish tidal marsh:** salt marshes along Big Bend; has low wave energy

National land cover classification schemes

The previously mentioned classification schemes were created specifically for Florida or the southeastern United States. National classification schemes often classify land cover based on vegetation type rather than by species. The Classification of Wetlands and Deepwater Habitats of the United States, developed by Cowardin et al. (1979) for the U.S. Fish and Wildlife Service, follows this type of general scheme. Relevant classifications include the following.

System: Estuarine (E): impacted by both seawater and freshwater runoff
- **Subsystem: Intertidal (2):** exposed substrate that is flooded by tides
  - **Class: Emergent wetland (EM):** dominated by herbaceous rooted plants, many of them perennial
    - **Subclass: Persistent (1):** plant species persist until the beginning of the next growing season (includes salt marshes)
  - **Class: Scrub-shrub wetland (SS):** dominated by woody vegetation <6 m (19.6 ft) high
    - **Subclass: Broad-leaved evergreen (3):** woody vegetation includes mangroves and other salt-tolerant trees, such as buttonwood

Class: Forested wetland (FO): dominated by woody vegetation >6 m (19.6 ft) high
Subclass: Broad-leaved evergreen (3): see above

The National Vegetation Classification Standard (NVCS, usnvc.org) is a hierarchical system designed by the Federal Geographic Data Committee (FGDC 2008). Relevant classifications include the following.

1. Forest and woodland
1.A Tropical moist forest
1.A.4 Mangrove (further classifications available based on location and species)
2. Shrubland and grassland
2.C. Temperate and boreal shrubland and grassland
2.C.6 Salt marsh (further classifications available based on location and species)

National Land Cover Data (NLCD) generated by the USGS uses its own classification system (Vogelmann et al. 1998, Fry et al. 2011). NLCD data sets are of limited utility to this study because the classifications do not differentiate between freshwater and coastal wetlands. Relevant classifications include the following.

4.3 Wetlands
4.31 Woody wetlands: soil periodically saturated with water and vegetation cover is >20% forest or shrubs
4.32 Emergent herbaceous wetlands: soil periodically saturated with water and vegetation cover is >80% perennial herbaceous

The National Oceanic and Atmospheric Administration's (NOAA's) Coastal Change Analysis Program (C-CAP) uses its own classification system. The original classification system was originally described by Klemas et al. (1993), and an updated summary is available in Dobson et al. (1995), which also explains how the land cover categories compare with those of Cowardin et al. (1997). Relevant classifications include the following

2.0 Wetland
2.3 Marine/estuarine emergent wetland
2.31 Haline: salt marsh where salinity is ≥30
2.32 Mixohaline: brackish marsh where salinity is 5–30
2.4 Estuarine woody wetland
2.41 Deciduous
2.411 Forest
2.412 Scrub–shrub
2.413 Dead
2.42 Evergreen
2.421 Forest
2.422 Scrub–shrub
2.423 Dead
2.43 Mixed
2.431 Forest
2.432 Scrub–shrub
2.433 Dead

Several of the classification schemes in Florida have crosswalk tables that show equivalent land cover categories among multiple schemes. Due to varying levels of specificity, categories may need to be combined or subdivided in order to translate between schemes. As part of the creation of the Florida Land Cover Classification System, crosswalk tables were made between this scheme and classification schemes from FWC, FLUCCS, and WMD modifications of FLUCCS (Kawula 2009).

Land cover mapping data in Florida

Land use data in Florida are available from a variety of regional, state, and national sources. A listing of data providers is compiled Table 1.3 and summarized in further detail below. This summary is also inclusive of some organizations that modify, enhance, and compile data generated by other providers. Land cover assessments generally relied on the use of satellite imagery or aerial photography. Land use classification schemes vary among agencies.

National land cover data sets

For more than 30 years, the National Wetlands Inventory (NWI) generated and updated highly detailed wetland maps following the Cowardin et al. (1979) classification scheme using a variety of methods and data sources, including aerial images (USFWS 2010). NWI maps are now made available online at www.fws.gov/wetlands/index.html.

The National Gap Analysis Program (GAP), run by the USGS, links together geographic layers of land cover, vertebrate species distribution data, and land conservation status (gapanalysis.usgs.gov). Data sets were created using multiseason Landsat ETM+ (Enhanced Thematic Mapper Plus) imagery from 1999 through 2001 with digital elevation model (DEM) derived datasets to model vegetation. General land cover classes from the

Table 1.3. Selected large-scale providers of coastal wetland land cover data in Florida

Program	Affiliation, region of map extent	Data origin, most recent data	Classification scheme	Reference
National Wetlands Inventory (NWI)	USFWS, national	Composite of multiple data and aerial image sources, 1970s to 2000s	Cowardin et al. 1979	USFWS 2010; www.fws.gov/wetlands
National Gap Analysis Program (GAP)	USGS, national	Southeast Gap Analysis Project, 1999–2001	NatureServe 2007, FGDC 2008	gapanalysis.usgs.gov/
Southeast Gap Analysis Project	USGS and North Carolina State University, southeastern U.S.	Landsat ETM+ and DEM models used to model vegetation classes, 1999–2001	NatureServe 2007, FGDC 2008	www.basic.ncsu.edu/segap/index.html
Wetland Status and Trends	USFWS, national	Remote imagery and randomized sample plots, 2009	Cowardin et al. 1979	Dahl 2005, 2011; www.fws.gov/wetlands/Status-and-Trends/index.html
Coastal Change Analysis Program (C-CAP)	NOAA, national coastline	Landsat 5 TM satellite imagery, 2010	Dobson et al. 1995	coast.noaa.gov/ccapftp/#/
2003 Florida Vegetation and Land Cover	FWC, Florida	Landsat ETM+ satellite imagery, 2003	Gilbert and Stys 2004	Stys et al. 2004, Kautz et al. 2007; ocean.floridamarine.org/mrgis/
Florida Water Management Districts (WMD) Land Use Land Cover (LULC) maps	NWFWMD	Color infrared or true color aerial photography, 2012–2013	FDOT 1999	www.fgdl.org/metadataexplorer/explorer.jsp
	SRWMD	Color infrared or true color aerial photography, 2010–2011	FDOT 1999	www.srwmd.state.fl.us/index.aspx?NID=319
	SWFWMD	Color infrared aerial photography, 2011	FDOT 1999	www.swfwmd.state.fl.us/data/gis/
	SFWMD	Composite of multiple data sources (see SFWMD 2005 for full listing), 2008–2009 (limited extent available for 2011–2013)	FDOT 1999, SFWMD 2009	my.sfwmd.gov/gisapps/sfwmdxwebdc/
	SJRWMD	Color infrared aerial photography, 2009	FDOT 1999, SJRWMD 2009	www.sjrwmd.com/gisdevelopment/docs/themes.html
FWC compilation of WMD mangroves and salt marshes	FWC, Florida	Compilation of WMD data, 1999–2011	FDOT 1999	geodata.myfwc.com/
Gulf of Mexico Data Atlas	NOAA, Gulf of Mexico coast and all of Florida	Mangrove data from FWC compilation of WMD data, wetlands data from NWI, 2000–2005	Mangrove data: FDOT 1999, NWI data: Cowardin et al. 1979	gulfatlas.noaa.gov/
Cooperative Land Cover (CLC) map	FNAI and FWC, Florida	Compiled from FWC 2003 land cover (Stys et al. 2004), WMD, aerial photography, and local data collections, 2003–2011	FNAI 1990, FDOT 1999, Gilbert and Stys 2004, Kawula 2009	Knight et al. 2010; www.fnai.org/LandCover.cfm

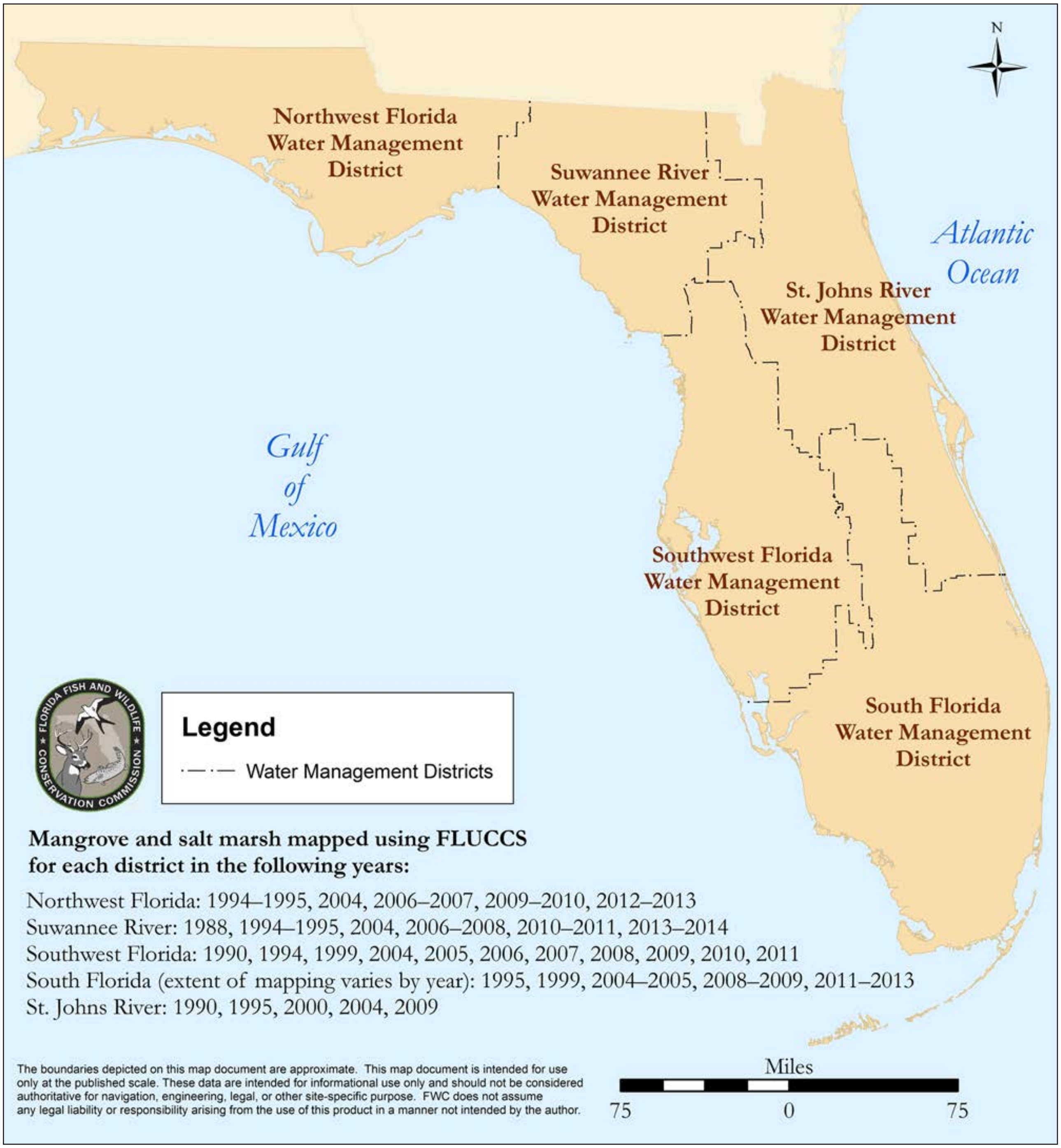

Figure 1.9. Water management districts in Florida.

National Land Cover Data were used (Vogelmann et al. 1998) as well as NatureServe's more specific terrestrial ecological classifications (NatureServe 2007). National GAP data sets are a compilation of data from regional GAP projects; Florida was a component of the Southeast Gap Analysis Project, which was a collaboration between North Carolina State University and the USGS (www.basic.ncsu.edu/segap).

The U.S. Fish and Wildlife Service (USFWS) Wetlands Status and Trends program quantifies the extent of wetlands in the conterminous United States through remote sensing, randomized ground sampling, and statistical estimates (Dahl 2006, 2011). The most recent analysis compares changes in wetland extent from 2004 through 2009 (Dahl 2011) and an older examination of wetlands from 1985 to 1996 is specific to Florida (Dahl 2005).

The Coastal Change Analysis Program (C-CAP), run by the National Oceanic and Atmospheric Administration's Office for Coastal Management, provides regional land cover change information for the coastal United States. Data are acquired via Landsat 5 TM satellite images and classified according to a C-CAP classification scheme (Dobson et al. 1995). For Florida, land cover and trend analysis data are available for 1996, 2001, 2006, and 2010. C-CAP offers downloadable data sets (coast.noaa.gov/ccapftp/#/) and an online mapper (www.coast.noaa.gov/ccapatlas/) that provides county-specific maps and analysis of changes in the extent of freshwater and saltwater marshes.

Statewide and regional land cover data sets

FWC created land cover maps based upon Landsat TM 1985–1989 imagery (Kautz et al. 1993) and completed an updated version based on Landsat ETM+ 2003 imagery (Gilbert and Stys 2004, Stys et al. 2004). The similar methodology used to create the two maps enabled the comparison and analysis of land use change between the two time periods (Kautz et al. 2007).

The Florida water management districts periodically complete their own assessments of land use and land cover (LULC) in their jurisdictions (Figure 1.9). Land cover analysis is based on remote imagery, and classifications are based on FLUCCS (FDOT 1999) categories, sometimes with slight modifications (SFWMD 2009, SJRWMD 2009). Land cover mapping years vary among districts (Figure 1.9). District LULC data are available on the district websites (Table 1.3). Compiled WMD maps of mangrove and salt marsh extent from 1999 through 2011 are available at the FWC Marine Resources Geographic Information System (MRGIS) (ocean.floridamarine.org/mrgis). The WMD land cover maps are often used as the basis for land cover maps generated by other governmental agencies.

NOAA's Gulf of Mexico Data Atlas website (gulfatlas.noaa.gov/) compiles data from other sources. The data atlas includes an online mapping program that enables the viewing of compiled WMD coastal wetland data and NWI wetland land cover data.

The Cooperative Land Cover Map (CLC) was developed as a collaboration between FNAI and FWC to support the goals of the Florida Comprehensive Wildlife Conservation Strategy (FWC 2005, Knight et al. 2010). The CLC project compiled data from various sources and integrated them using aerial photography and local data collections. Data were obtained from the 2003 FWC land cover data set, Florida WMD LULC data, aerial photographs, and interviews with local experts (Knight et al. 2010). Each data set was assigned a confidence category to determine its ranking over other data sets. Due to the diverse array of data sources, multiple land classification systems were used (FNAI 1990, FDOT 1999, Gilbert and Stys 2004). All classifications were crosswalked into the Florida Land Cover Classification System (Kawula 2009).

Table 1.4. Total acres (and hectares) of salt marsh and mangrove swamp in Florida. See Table 1.3 for details on data sources.

Habitat	Florida Water Management Districts LULC maps	FWC 2003 Florida Vegetation and Land Cover	Cooperative Land Cover version 3.2
Salt marsh	385,000 (155,800 ha)	447,400 (181,060 ha)	378,690 (153,250 ha)
Mangrove	606,040 (245,260 ha)	588,320 (225,940 ha)	571,750 (231,380 ha)
Scrub mangrove	-	6,520 (2,640 ha)	-
Keys tidal rock barren	-	-	8,520 (3,450 ha)

Comparison of selected land cover data

Statewide assessments of total salt marsh and mangrove acreage vary among sources. Image types, resolution, classification schemes, minimum mapping units, and interpretation methods vary among agencies, leading to differences in overall acreage assessments. An example of variability in statewide assessments of total acreage of salt marshes and mangroves is shown in Table 1.4. Note some of this variability likely reflects different years of mapping efforts.

Figures 1.10 and 1.11 demonstrate differences between selected land cover data sets. A small section of coastal wetlands in northeast Tampa Bay (Figure 1.10) shows a high degree of similarity between polygon land cover maps developed by the SWFWMD, the Cooperative Land Cover program, and the National Wetlands Inventory. In this region, the NWI category of *persistent estuarine intertidal emergent wetland* directly corresponds to salt marsh and *estuarine intertidal wetlands with scrub–shrub broad-leaved evergreens* directly corresponds to mangroves. More patchy classifications are evident in the raster classification schemes, particularly in the maps created by the National Gap Analysis Program (GAP). Although GAP does have a salt marsh classification category, most of this area was classified as other types of vegetation (Figure 1.10).

Variability between these land cover classification maps becomes more evident in a section of the Ten

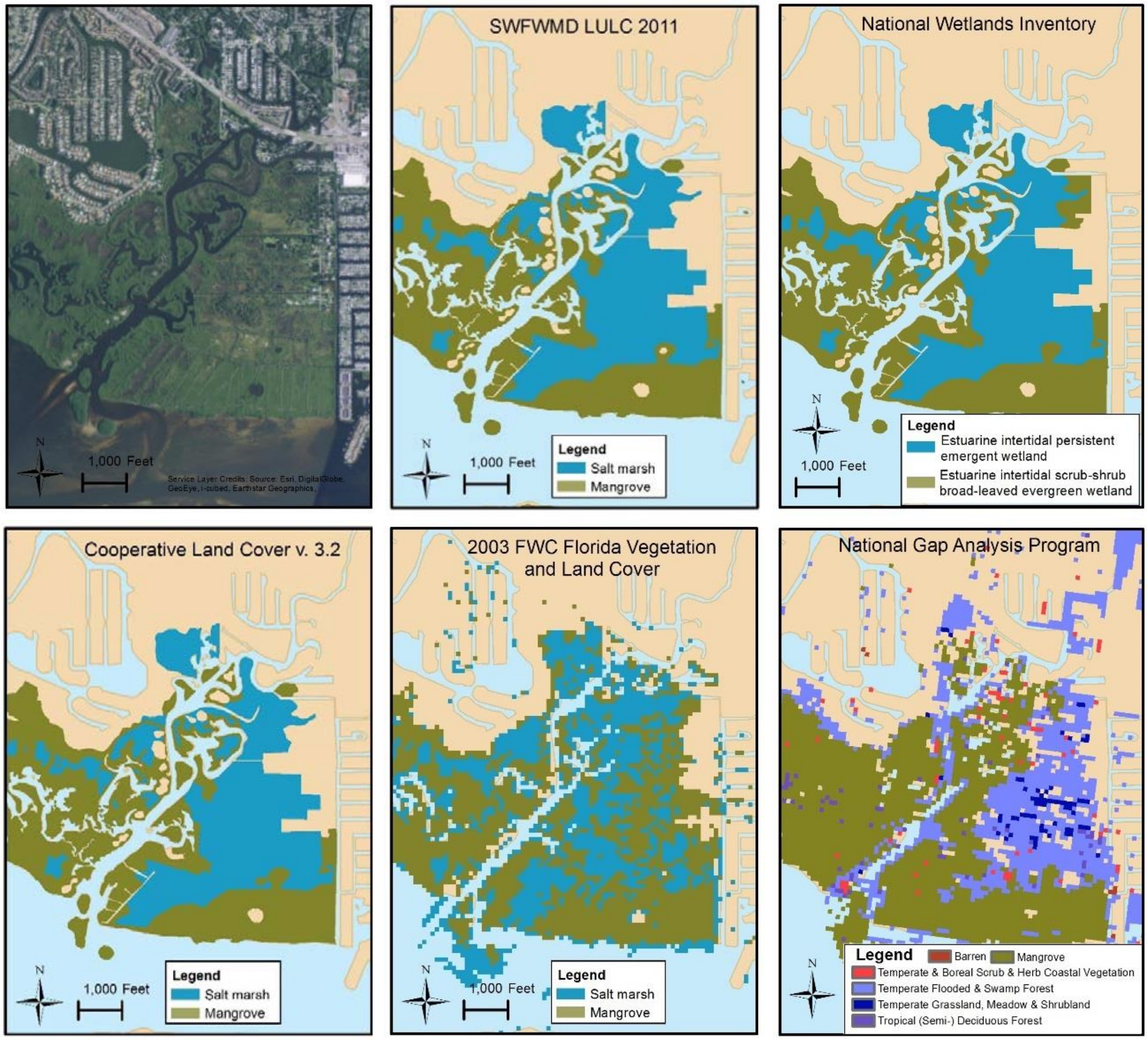

Figure 1.10. Northeast Tampa Bay example of raster and polygon coastal wetland mapping data from various sources. See Table 1.3 for details on data sources.

Thousand Island region in Southwest Florida (Figure 1.11). Maps generated by SFWMD and the Cooperative Land Cover Program are highly similar, since CLC maps utilize data generated by the water management districts as one of their data sources (Knight et al. 2010). The National Wetlands Inventory differentiates between scrub-shrub and forests of mangroves. Even when this differentiation is taken into account, however, the extent of persistent estuarine intertidal emergent wetland is less than that of salt marsh classified in the other maps. The raster 2003 FWC Florida Vegetation and Land Cover is again more fragmented yet presents similar distributions of salt marshes and mangroves, while the National Gap Analysis Program classifies much of the region as freshwater marshes.

Monitoring in coastal wetlands

Wetland monitoring is conducted intermittently throughout Florida through various in situ or remote sensing methods. Coastal wetland monitoring is typically completed in areas that are protected, such as state or national parks, or at sites of wetland mitigation or restoration projects (Figure 1.12). Rarely are these monitoring programs long-term, generally due to insufficient funding or resources (Fancy and Bennetts 2012). The minimum allotted time of monitoring for restoration or mitigation sites is typically 3–5 years, after which monitoring is discontinued because regulatory criteria have been met or funding is no longer available (Thayer et al. 2003, Lewis 2004, Lewis 2005, Lewis and Brown 2014). Although long-term funding is difficult to secure for prolonged monitoring projects, monitoring

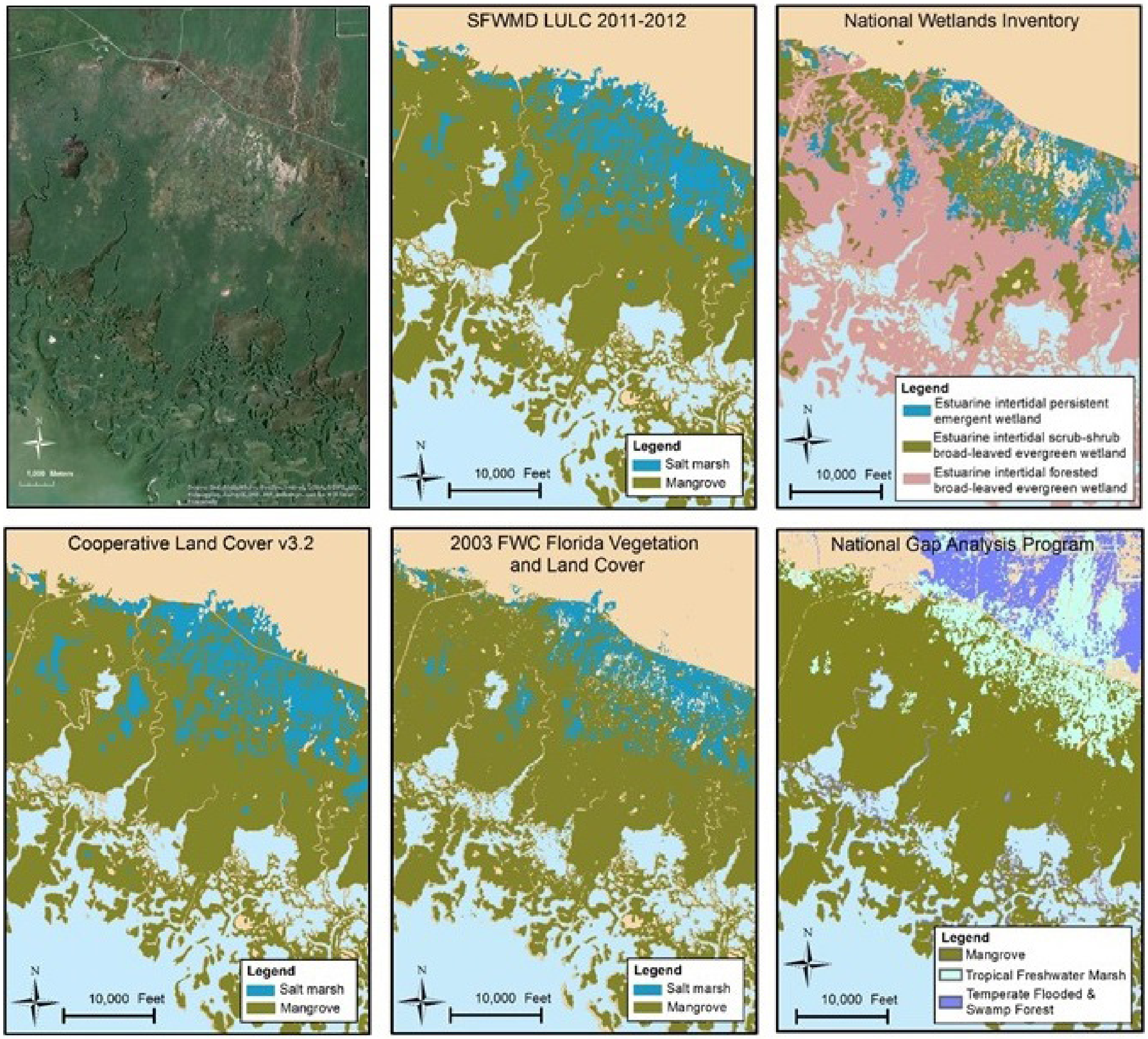

Figure 1.11. Ten Thousand Islands example of raster and polygon coastal wetland mapping data from various sources. See Table 1.3 for details on data sources.

Figure 1.12. A new salt marsh restoration project in Tampa Bay.

over long time scales is increasingly important due to regional uncertainties of how substrate accretion and vegetative growth will respond to sea-level rise, altered freshwater hydrology, and other disturbances. While periodic land cover mapping programs can document changes in habitat and land cover, more subtle, species-specific changes in vegetation coverage within each habitat are best captured by on-the-ground monitoring. Ecological monitoring is also critical in identifying impacts of disturbances, climate change, and altered hydrologic patterns on ecosystem services provided by coastal wetlands.

The protocols used to monitor wetlands differ depending on specific project goals, management questions, and type of wetland. Likewise, methods for monitoring restored or created wetlands can differ between local, state, and federal agencies and nongovernmental organizations. These methodologies also differ greatly from

Table 1.5. Examples of monitoring procedures used for coastal wetlands in Florida.

Name	Association, Region	Focus	Reference
Wetland Assessment Procedure (WAP)	SFWMD and Tampa Bay Water (TBW), Florida	Monitoring isolated wetlands for management considerations	SFWMD and TBW 2005
Wetland Rapid Assessment Procedure (WRAP)	SFWMD, Florida	Rating index for monitoring temporal changes in altered wetlands	Miller and Gunsalus 1997
Monitoring and Assessment Plan (MAP)	Comprehensive Everglades Restoration Plan (CERP), South Florida	MAP is used as a tool to assess CERP	CERP 2004
Uniform Mitigation Assessment Method (UMAM)	Florida Department of Environmental Protection (FDEP), Florida	Methods to assess mitigated habitats in Florida	FDEP 2012
South Florida/Caribbean Network (SFCN) Vital Signs Monitoring Plan	National Park Service (NPS) SFCN, South Florida	Monitor vital signs of national park ecosystems in SFCN, including coastal wetlands	Patterson et al. 2008
Vital Signs Monitoring in the Southeast Coast Inventory & Monitoring Network (SECN I&M)	NPS SECN I&M, Northeast Florida	Monitor vital signs of national park ecosystems in SECN, including coastal wetlands	DeVivo et al. 2008
Nutrient Criteria Technical Guidance Manual: Wetlands	U.S. Environmental Protection Agency (EPA), national	Assessing nutrient status and developing nutrient criteria for wetlands	USEPA 2008
Hydrogeomorphic Methodology (HGM)	U.S. Army Corps of Engineers, EPA, Federal Highway Administration, Natural Resources Conservation Service, and U.S. Fish and Wildlife Service, national	Evaluates wetland functionality and predicts impacts of future changes	USACE 2010
NERRS System-Wide Monitoring Program (SWMP) Vegetation Monitoring Protocol	National Estuarine Research Reserve System (NERRS), national, with 3 reserves in Florida	Long-term estuarine and coastal wetland vegetation monitoring	Moore 2013
Coastal Blue Carbon	The Blue Carbon Initiative, international	Methods to assess carbon stocks and emissions of coastal wetlands and seagrass	Howard et al. 2014
Ecological Mangrove Rehabilitation: A field manual for practitioners	Mangrove Restoration, international	Practical international guide for mangrove rehabilitation and monitoring	Lewis and Brown 2014
Methods for Studying Mangrove Structure	UNESCO Scientific Committee on Ocean Research, international	Field methods to quantify mangrove structure	Cintron and Novelli 1984
Remote sensing procedures (general)	Varied	Use of satellite data, aerial photographs, and LiDAR to monitor wetlands	Kasischke and Bourgeau-Chavez 1997, Ozesmi and Bauer 2002, Dahl 2006, Klemas 2011

those used in long-term monitoring, which seeks to determine long-term trends and responses to natural and anthropogenic changes to the environment. A list of selected monitoring protocols used in Florida is provided in Table 1.5. For a more thorough review of wetland monitoring and sampling methods, see Fennessy et al. (2004), Thayer et al. (2005), or Haering and Galbraith (2010).

Remote sensing can also be used to inventory and monitor wetlands and provides the advantage of wide coverage at lower cost than in situ sampling. Digital satellite data are easily integrated into GIS software, are available for large areas, and supply coverage for annual monitoring for a relatively low cost (Ozesmi and Bauer 2002). For detailed analysis of wetlands, however, aerial photography is preferred because it is easier to differentiate the spectral signatures of various habitats (Ozesmi and Bauer 2002). Remote sensing techniques and methodology vary widely depending on the technology used, research questions, and habitat variability (Kasischke and Bourgeau-Chavez 1997, Ozesmi and Bauer 2002, Dahl 2006, Klemas 2011).

Long-term monitoring of Florida coastal wetlands: examples of two methodologies

1. THE GUANA TOLOMATO MATANZAS NATIONAL ESTUARINE RESEARCH RESERVE

NIKKI DIX, Guana Tolomato Matanzas National Estuarine Research Reserve

The monitoring methods of the Guana Tolomato National Estuarine Research Reserve (GTMNERR) are provided here as an example of an extensive, long-term monitoring program for coastal wetlands. The GTMNERR's primary monitoring goal is to improve understanding of the ecological characteristics of the dynamic community and to discern the impacts of local and global changes on the estuarine ecosystem. Following the National Estuarine Research Reserve System (NERRS) protocols for biological monitoring (Moore 2013), specific objectives are to:

1. Establish permanent emergent intertidal vegetation monitoring sites throughout the estuary spanning the entire north–south gradient of the reserve.
2. Characterize patterns in vegetation species composition, abundance, and cover at multiple temporal and spatial scales.
3. Determine the influence of environmental characteristics on vegetation patterns.
4. Determine the impact of large-scale environmental changes (e.g., climate change, sea-level rise) on the emergent intertidal vegetation community.

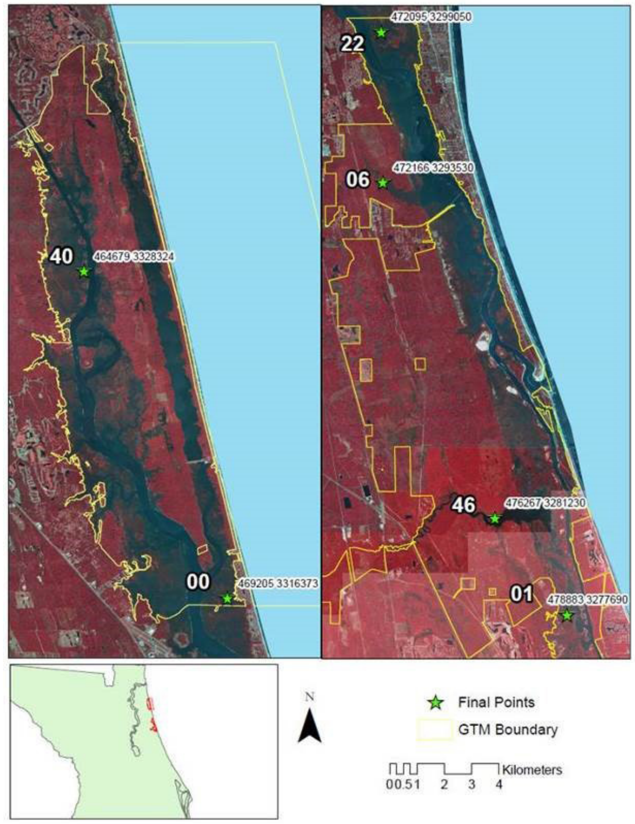

Figure 1.13. Locations of the six emergent-vegetation monitoring sites. At Moses Creek (06) and Pellicer Creek (46) transects extend to the terrestrial transition zone.

Emergent marsh vegetation monitoring

The GTMNERR's emergent intertidal vegetation monitoring protocol is a combination of the NERRS Biological Monitoring protocols (Moore 2013), the National Park Service Southeast Coastal Network (SECN) protocols (Asper and Curtis 2013a, Curtis et al. 2013), and the Louisiana Department of Natural Resources Coastal Resource Division protocol (Folse and West 2004). The SECN protocol was developed in collaboration with NERRS scientists to ensure monitoring compatibility in salt marsh communities throughout the southeastern U.S. Atlantic coast. Sites were selected using a spatially balanced random-sample design developed by the SECN (Byrne 2012).

After examination of potential sampling sites, six permanent emergent transition zone sampling sites were chosen that met the selection criteria (Figure 1.13). Within each of the six sites, three replicate stations were established within a 70-m buffer. Because southeastern U.S. low marshes are easily disturbed by trampling (Turner 1987), permanent platforms were constructed to minimize foot traffic (Figure 1.14). Within each site, three replicate boardwalk systems were constructed, each consisting of two boardwalks, one approximately 9 m long and one approximately 3 m long (both oriented perpendicular to the marsh edge), which are connected during sampling with a removable cross-piece. Each station consists of five permanent 1-m^2 vegetation plots marked with PVC at opposite corners.

At two of the sites (Moses Creek [06] and Pellicer Creek [46]), three replicate transects were extended from the boardwalks to the terrestrial transition zone. Ten permanent 1-m^2 vegetation plots were marked with PVC on each replicate transect. Plots were evenly distributed beginning at 10 m from the shoreline at 10-m (Moses Creek) or 30-m (Pellicer Creek) intervals.

In each vegetation plot, maximum canopy height is determined by averaging the height of the five tallest individuals of the dominant species. Percent cover is de-

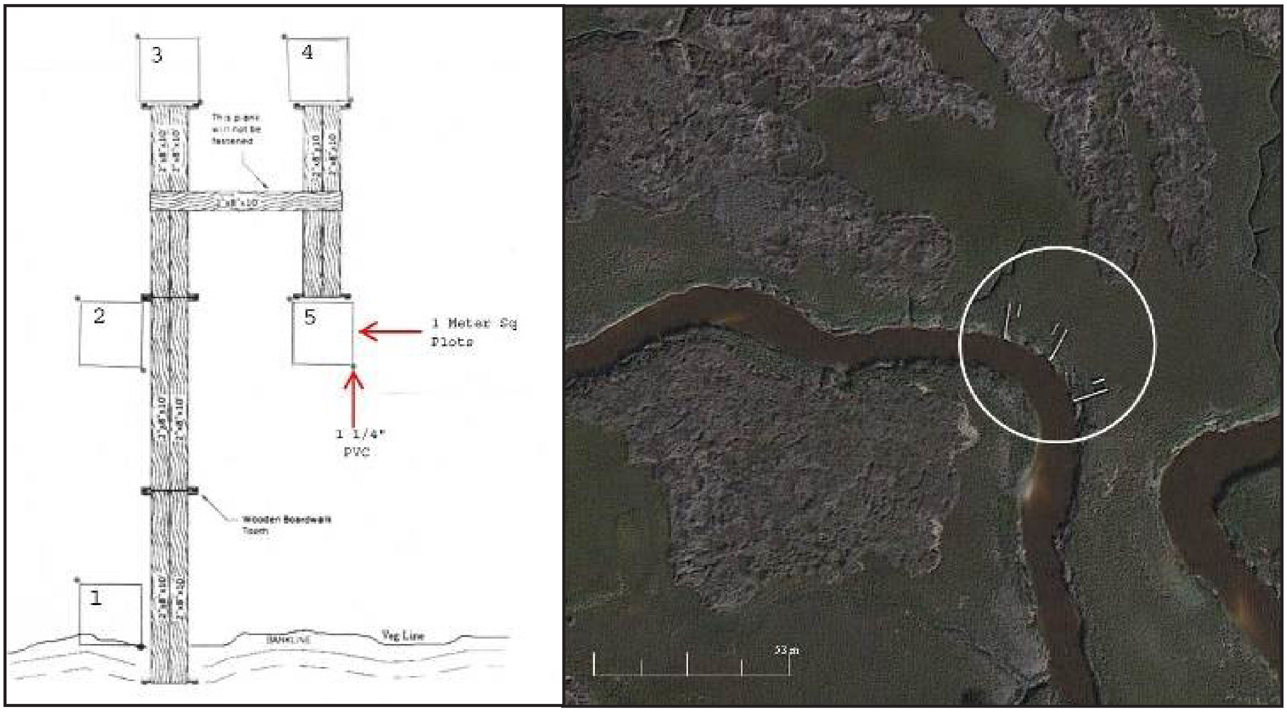

Figure 1.14. Schematic, left, of emergent vegetation platform and emergent platforms, right, located at Moses Creek (06) as seen from aerial imagery. Figure credit: GTMNERR

termined by visual estimates (in 5% increments) in the field as well as by the acquisition of close-to-earth nadir (downward facing) images processed in SamplePoint software (Booth et al. 2006). A lightweight collapsible camera stand (2 m high with a 1- × 1-m base) fabricated to the specifications outlined by Booth et al. (2004) and Curtis (2013) is used to acquire images in the field using a digital SLR camera with a remote trigger (Figure 1.15). The nadir images are cropped with Adobe Photoshop Elements 9 to the inside corners of the camera stand base for a 1-m^2 photo plot (Figure 1.16).

Images are imported into SamplePoint, in which 100 randomly generated pixels are classified to the species level by a biologist. More information on SamplePoint and the image classification process can be found at www.samplepoint.org/SamplePointTutorial.pdf. For species with cover less than 5%, a cover of 1% is assigned in the field. If a species is missed in the field but identified by SamplePoint, or vice versa, a cover of 1% is assigned in the laboratory.

Salt marsh platforms were installed in 2011, and initial measurements were conducted in 2012. Due to a lack of detailed phenological information of salt marsh vegetation in the GTMNERR, sampling was done monthly throughout 2014 to determine peak growing season. Sampling has continued annually, during peak growing season. The intention is to sample salt marsh sites for at least 50 years. Unfortunately, shore-to-upland transect monitoring behind the boardwalks resulted in degradation to the marsh from trampling. Therefore, ground-based shore-to-upland transect monitoring will be postponed until a solution (and necessary funds) for sampling without damaging the marsh can be found.

Figure 1.15. Assembled lightweight camera stand for close-to-earth remote sensing (left) and acquisition of nadir images (right). Photo credit: GTMNERR

Figure 1.16. Vegetation plot images dominated by, from left, *Spartina alterniflora*, *Batis maritima,* and *Juncus roemerianus*, cropped and prepared for processing in SamplePoint. Photo credit: GTMNERR

Figure 1.17. Biologist Jason Lynn lowers the pins of a surface elevation table, or SET. Photo credit: GTMNERR

GTMNERR emergent marsh sediment elevation monitoring

At each of the 18 emergent marsh vegetation monitoring stations, a deep-rod surface elevation table (SET) was installed roughly 6 m from the subtidal creek between the two platforms (Figure 1.17; Cahoon et al. 2002a, 2002b). SETs were installed in 2011, but initial measurements were delayed until 2013. Beginning in January 2014, SET monitoring was conducted monthly for one year, concurrently with salt marsh vegetation monitoring.

Sediment elevation is measured along the arm of the SET by lowering nine pins (Figure 1.17) to the marsh surface and measuring the distance from the arm to the top of the pin. Pin measurements are taken in all four cardinal directions from rod for a total of 36 pin measurements at each SET station.

Beginning in June 2013, concurrently with initial SET measurements, nine accretion/erosion plots per site were established using feldspar horizons (Asper and Curtis 2013b). Feldspar horizons were established by sprinkling white feldspar clay on the wetland surface, where it serves as a visible white marker horizon for cryogenic cores that are taken annually from the date of installation to assess sediment accretion (Cahoon et al. 1996).

GTMNERR mangrove monitoring

Following Moore (2013), the GTMNERR has identified two sites for mangrove monitoring, one on the Guana Peninsula at the northernmost extent of the range of *A. germinans* and one near Matanzas Inlet, where *A. germinans* is prevalent. Protocols are still under development, but initial monitoring efforts have been structured as follows. Each site has two replicate transects consisting of 5 10- × 10-m whole plots (100 m^2) distributed evenly along the transect with five 1-m^2 subplots in each whole plot (total of 25 1-m^2 subplots on each transect) (Figure 1.18).

Mangrove community dynamics are examined at three scales (whole plot, subplot, and individual tree), with specific metrics identified for each level. Together, these multiscale metrics provide comprehensive information on the scrub or shrub mangrove community while minimizing plot disturbance. Specific metrics are described for each level in Moore (2013) as follows:

- **Whole plot:** General characteristics of each of five whole plots along the transect are measured including percent cover (mangrove spp. vs. other) and soil pore-water salinity and temperature (both measured at the time of collection in the field).

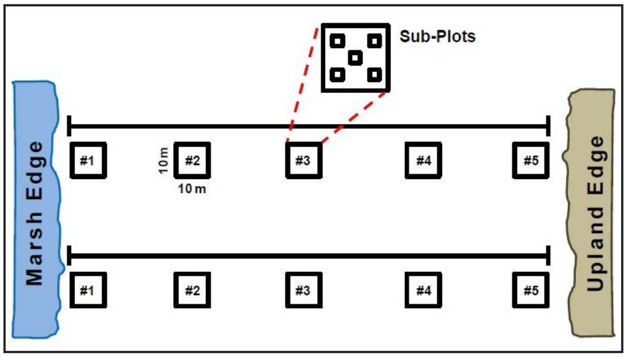

Figure 1.18. Layout of whole plots and subplots along a transect. Figure credit: Moore 2013

- **Subplot:** For each subplot, percent cover (mangrove spp. vs. other) is measured. Mangroves are identified by species and stage (shoot = no branches; tree = has branches). Trunk diameter (mm; ~2 cm above the sediment) and canopy height (cm) are measured for each individual tree. Note: this is different from the standard measure of trunk diameter used for larger mangrove trees, which is diameter at breast height (DBH), measured 1.4 m above the ground surface (Cintron and Novelli 1984).
- **Individual trees:** A subsample of up to 10 of the largest trees for each mangrove species in each whole plot are tagged and the following measurements taken to examine tree architecture (see Moore 2013 for further explanation):

1. Canopy height (cm): distance from ground surface to top of canopy
2. Trunk formation: single or multiple trunk
3. Trunk diameter (mm): diameter just above sediment (~2 cm); if multiple trunks, the largest trunk is measured
4. Clear height (cm): height from sediment to first branch
5. Canopy, wide axis (cm): canopy width at the widest point
6. Canopy, narrow axis (cm): perpendicular to the wide axis, canopy width at the widest point
7. Canopy offset (cm): the horizontal distance between the trunk and the intersection of the wide and narrow canopy axes
8. Ground cover: Species present in the area under the tree canopy

The methods described above will enable study of spatial patterns in vegetation at a variety of spatial and temporal scales within Florida NERR habitats. Long-term monitoring of these sites will facilitate determination of the impact of climate change and sea-level rise on abiotic parameters and emergent intertidal vegetation.

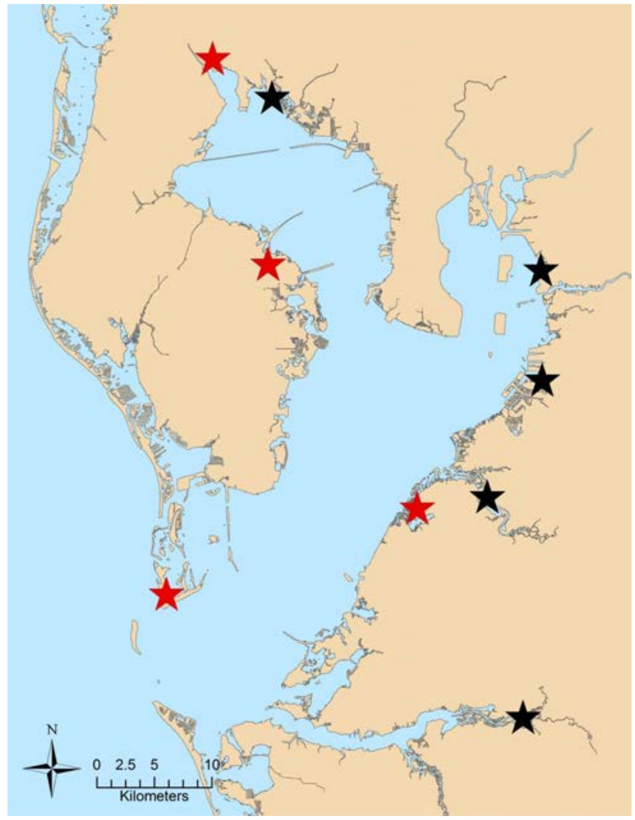

Figure 1.19. Tampa Bay CCHA monitoring sites, shown as black stars (established in 2015) and red stars (established in 2016).

2. CRITICAL COASTAL HABITAT ASSESSMENT MONITORING IN TAMPA BAY

LINDSAY CROSS, Tampa Bay Estuary Program

Methods developed by Doug Robison (Environmental Science Associates), Pamela Latham (Research Planning Inc.), Lindsay Cross, and David Loy (Atkins North America)

The Tampa Bay Estuary Program initiated a long-term monitoring program in 2015 for coastal habitats as part of a larger effort to manage, restore, and protect habitats critical to the ecological function of the Tampa Bay estuary (Sherwood and Greening 2012). The objective of the Critical Coastal Habitat Assessment (CCHA) is to “develop a long-term monitoring program to assess the status, trends, and ecological function of the mosaic

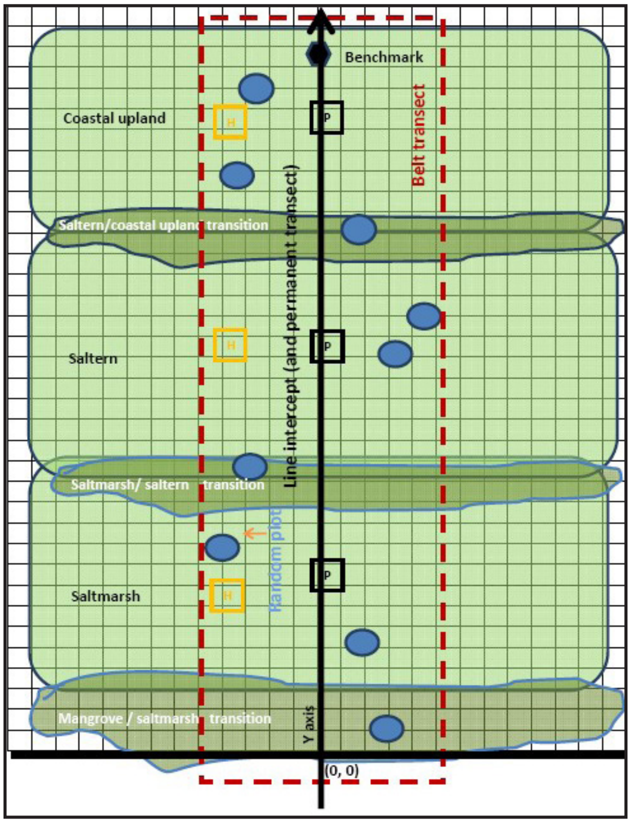

Figure 1.20. Stratified random sampling design with random plots (blue circles) in each vegetation strata (not to scale). Sampling design includes belt transect, line intercept, and individual sample plots. Yellow and black squares indicate soil core and Feldspar horizon (H) and piezometer (P) locations, respectively.

of critical coastal habitats to detect changes due to natural and indirect anthropogenic impacts including sea-level rise and climate change, and improve future management of habitats." This effort will be accomplished through development of a long-term fixed transect program that will characterize baseline (2015–2016) status and detect changes in habitat and ecosystem function over time. Monitoring locations were initially established in 2015 at five sites around the Tampa Bay watershed (Figure 1.19) in protected areas with minimal disturbance that have a full complement of emergent tidal wetland communities including mangrove, salt marsh, salt barrens, and coastal uplands. The CCHA is designed to be a long-term assessment with monitoring occurring every 3–5 years in perpetuity. Transects include randomized quadrats for detailed species analysis as well as a belt transect that that enables verification with aerial photointerpretation and vegetation mapping. The sampling approach is outlined in Figure 1.20.

Figure 1.21. Location of transect at Upper Tampa Bay Park, including mangrove, salt marsh, salt barren, pond, and upland habitats.

Elevation and abiotic parameters

- **Elevation:** Permanent benchmarks were established at the landward and seaward extent of the transect. Elevations were then surveyed along the entire transect at 5-ft (1.5-m) intervals following the FDEP standards for elevation surveys of beach profiles (FDEP 2014). Real-time kinematic (RTK) GPS technology was also evaluated as a survey technique.
- **Interstitial salinity:** Pore water was collected with a one-way hand pump from a freshly augured pit and measured using a conductivity meter, specific gravity meter, or handheld refractometer. Care was taken to ensure that pore water was collected at similar tidal stages across all monitoring sites.
- **Soils:** Soil samples were collected at the same locations as the vegetation samples and feldspar horizons and analyzed for total percent organic content and sediment grain size.
- **Feldspar horizons:** Feldspar marker horizons were placed within each vegetation zone within a 50- × 50-cm plot and at a thickness of approximately 0.25 inch (0.6 cm). Steel rebar was driven into the soil to mark the corners of the feldspar plot. Accretion will be monitored by coring within the feldspar plot every 6–12 months. It is anticipated that four sampling events can be conducted within each marker before replacement will be necessary due to washout in higher-energy areas and bioturbation by fiddler crabs.
- **Location markers:** GPS coordinates were recorded in each vegetation zone and at transitions. Available aerial photography (Figure 1.21), combined with photointerpretation and ground truthing, was used to develop detailed GIS habitat maps of each transect site.

Vegetation monitoring

- **Belt transect:** A belt transect (red dashed outline, Figure 1.20) was established along the entire transect. Percent cover by community type (e.g., mangroves, salt marsh, salt barren, coastal upland) was recorded for each zone.
- **Quadrat sampling along belt transects:** Basal percent cover of vegetation (the area occupied by the base of the plant) was recorded within 0.5- × 0.5-m quadrats along the entire permanent transect (solid black line, Figure 1.20).
- **Randomized quadrats:** Plots 1-m^2 (blue shaded circles, Figure 1.20) were randomly assigned in each habitat and transition zone based on XY coordinates derived from a random-point generator. Species and basal percent cover were recorded for all vegetation to provide measurements of density, frequency, and relative species dominance for each stratum (Figure 1.22).
- **Forest sampling:** Within the mangrove zone, tree sampling data were collected using the Point-Centered Quarter method (PCQ, Cottam and Curtis 1956). In the PCQ method, the distance to the closest tree, species of that tree, and the DBH of that tree are determined within each of four directional quarters. Tree height for the closest tree in each quarter was also collected using either a clinometer (in areas of sparse tree coverage) or an extendable survey rod (in areas of dense tree coverage). Finally, an estimate of percent canopy coverage was obtained using a densitometer.

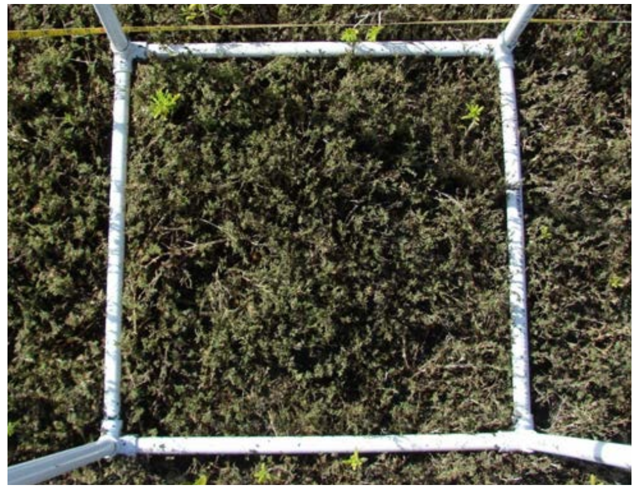

Figure 1.22. Assessing percent cover of vegetation in salt marsh and mangrove portions of the transect.
Photo: Tampa Bay Estuary Program.

Faunal monitoring

Faunal monitoring was conducted in each of the 1-m^2 randomly selected plots. The number of periwinkle snails (*Littorina* spp.) as well as fiddler crabs (*Uca* spp.) and their burrows were counted (Figure 1.23). In the forested zones, observed species of arboreal crabs were also recorded.

Figure 1.23. Atlantic sand fiddler crab (*Uca pugilator*).
Photo: Tampa Bay Estuary Program.

Phase 2 expansion of monitoring

A second phase of the project was initiated in 2016 in partnership with TBEP and the Florida Fish and Wildlife Conservation Commission Fish and Wildlife Research Institute. This phase implemented the same methods but incorporated four additional sites around the watershed, including some that have had hydrologic or other anthropogenic impacts, including restoration. This expanded the breadth of data acquired and may address whether habitats in disturbed sites react differently to sea-level rise than areas with less impacts. These additional four study sites are

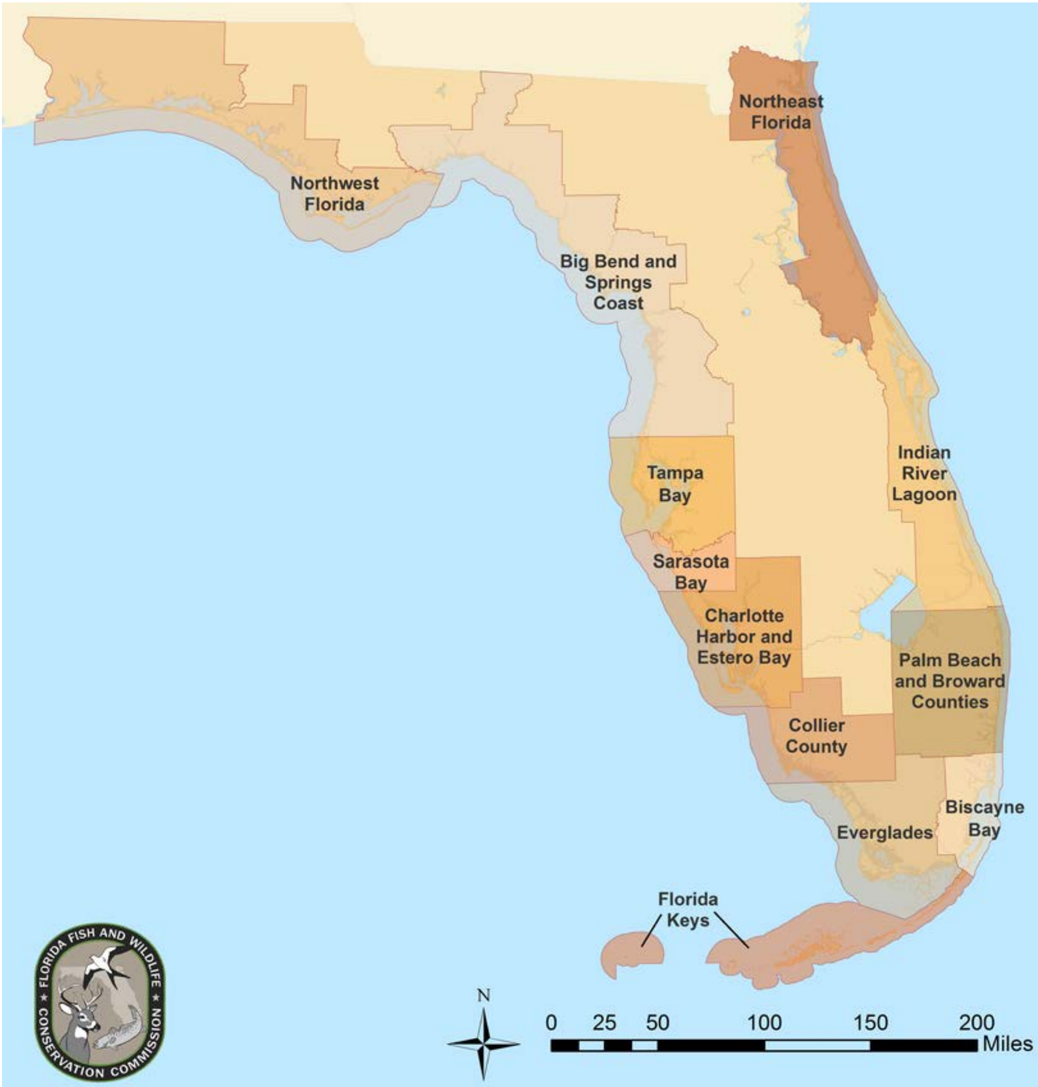

Figure 1.24. Regions of focus for the CHIMMP report chapters.

distributed across western Tampa Bay (see Figure 1.19). In addition, a multimedia training manual will be created that outlines, step-by-step, the methods and field and laboratory protocols used in the Tampa Bay project. This manual, and the other project deliverables, can be used by other agencies in Florida and elsewhere in the Gulf of Mexico to implement similar long-term monitoring programs. Results of the CCHA will be used to inform future management and restoration of habitats in the Tampa Bay watershed, with the goal of improving long-term success of habitat acquisition, restoration, and management.

Monitoring resources

While the majority of coastal wetland monitoring methodologies focus on monitoring restoration or mitigation sites (Table 1.5), long-term studies provide valuable information on vegetative and substrate responses to climate change and sea-level rise. Habitat mapping information provides documentation of large-scale changes in land cover, while complementary in situ monitoring enables study of the fine-scale changes in species composition and sediment characteristics of salt marshes, mangroves, and associated coastal habitats.

Numerous online monitoring resources are available, including portals of compiled monitoring data, statewide and nationwide programs, and general monitoring resources. These resources include:

- Southeast Global Change Monitoring Portal
  my.usgs.gov/gcmp/
- Southeast Coastal Water Quality Monitoring Metadata Project Web Portal
  www.gcrc.uga.edu/wqmeta/
- Governors' South Atlantic Alliance Coastal Wetlands Monitoring Report and Database

southatlanticalliance.org/coastal-wetlands-monitoring-report-and-database/

- Gulf Coast Prairie Landscape Conservation Collective Gulf Coast Vulnerability Assessment: gulfcoastprairielcc.org/science/science-projects/gulf-coast-vulnerability-assessment/
- Mangrove, Tidal Emergent Marsh, Barrier Islands, and Oyster Reef section: gulfcoastprairielcc.org/media/28948/gcva_11162015_final-2.pdf
- Gulf Coastal Plains and Ozarks Landscape Conservation Collective Surface Elevation Table Inventory for the Northern Gulf of Mexico: gcpolcc.databasin.org/datasets/6a71b8fb60224720b903c770b8a93929
- EPA National Wetland Condition Assessment: www.epa.gov/national-aquatic-resource-surveys/national-wetland-condition-assessment
- EPA Wetlands Monitoring and Assessment: www.epa.gov/wetlands/wetlands-monitoring-and-assessment
- National Estuarine Research Reserve System vegetation monitoring overview and data: cdmo.baruch.sc.edu/get/vegetation_index.html
- Restore America's Estuaries Blue Carbon Resources: www.estuaries.org/bluecarbon-resources
- FDEP overview of the wetland and other surface water regulatory and proprietary programs in Florida: www.dep.state.fl.us/water/wetlands/docs/erp/overview.pdf
- FDEP State of Florida Wetland Program Plan (program under way since 2013): www.epa.gov/sites/production/files/2015-10/documents/fl-wpp-2013.pdf. Projects in this plan include the Florida Wetlands Integrity Dataset: www.aswm.org/pdf_lib/mapping_webinar/fl_wetland_integrity_dataset_humphreys_mahjoor_091615.pdf
- Mangrove Restoration and Monitoring Resources: www.mangroverestoration.com/html/downloads.html

Region-specific chapters

The remainder of this report documents region-specific ecosystems, monitoring, and mapping programs across Florida. The 12 CHIMMP regions are separated as shown in Figure 1.24. Each chapter includes a general introduction to the region, location-specific threats to salt marshes and mangroves, a summary of selected mapping and monitoring programs, and recommendations for future protection, management, and monitoring.

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