Chapter 8

Everglades

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Description of the region

The ecology and health of the Everglades are maintained by the quantity, quality, timing, and distribution of freshwater input. Historically, the Everglades was tightly linked to a large watershed that encompassed much of central and southern Florida (Figure 8.1). Water meandered down the circuitous Kissimmee River to Lake Okeechobee, where it spilled over the southern edge of the lake into an expansive sawgrass marsh. The sheet of surface water then slowly made its way south, supporting a variety of freshwater marshes in the interior and mangroves and salt marshes along the coast. The Everglades is bordered on the northwest by the Big Cypress Swamp and on the east by the Atlantic Coastal Ridge, which functions as a natural barrier to surface water flow. The interior ridge-and-slough landscape consists of dense stands of sawgrass (*Cladium jamaicense*) growing on ridges with a slightly higher elevation than the adjacent parallel sloughs. The sawgrass marsh is interspersed with bayhead and tropical hardwood hammock forests, or tree islands, that grow atop elevated limestone or woody peat outcrops (Armentano et al. 2002). Major hydrologic pathways through the Everglades include Taylor Slough, which flows into Florida Bay, and Shark River Slough, which flows into the Harney, Shark, and Broad rivers (Olmsted and Armentano 1997), which discharge to the Gulf of Mexico (Figure 8.2).

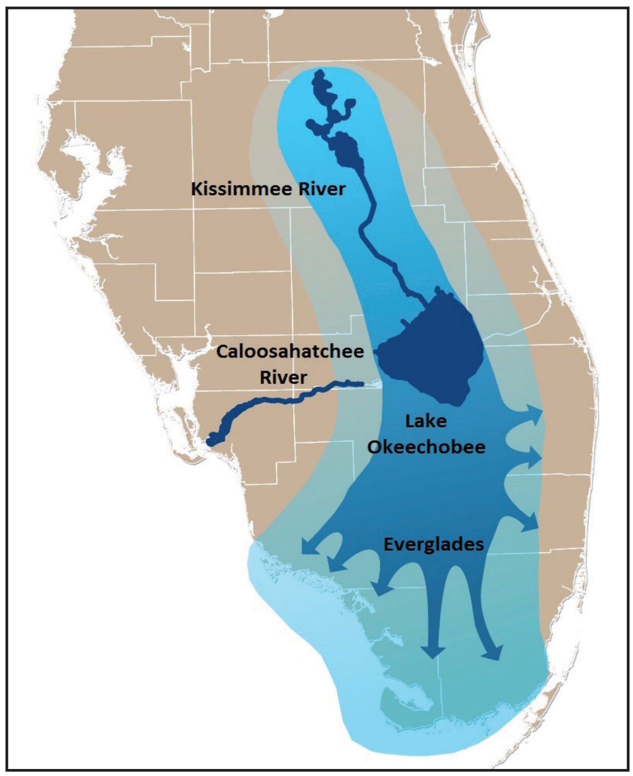

Figure 8.1. Historical flow of surface water in the South Florida watershed. Figure credit: Chris Anderson.

The low elevation and gentle topography of South Florida supports broad swaths of coastal wetlands (Figure 8.3). Mangroves line almost the entire coast of the Everglades, although in some locations they occur farther inland due to natural landscape patterns created by a complex of small streams. Salt marshes dominated by black needlerush (*Juncus roemerianus*) and smooth cordgrass (*Spartina alterniflora*) are found inland of these mangroves (Lodge 2010).

Small changes in elevation determine the distribution of vegetative communities. For instance, tropical hard-

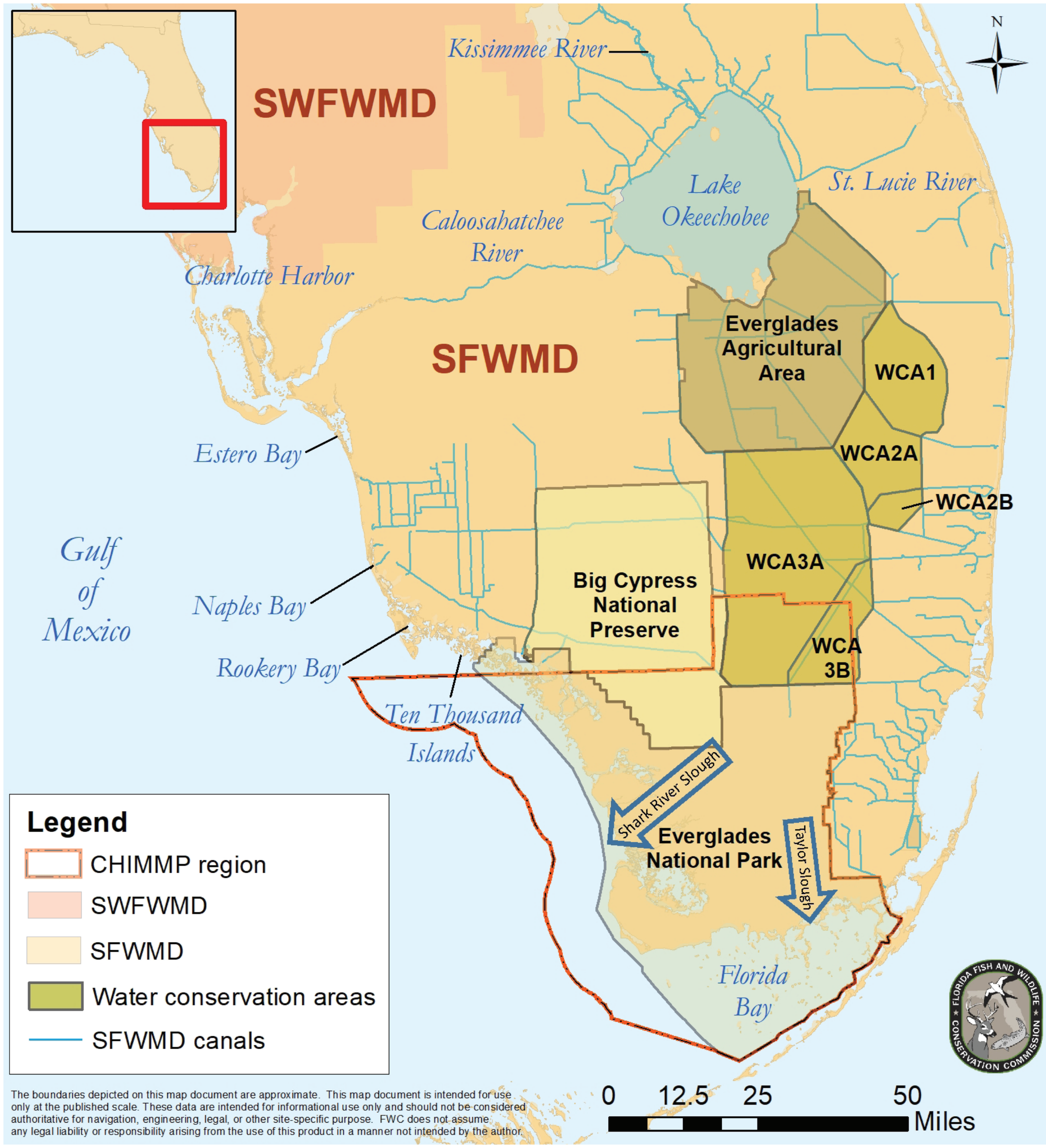

Figure 8.2. Major features of the South Florida watershed today.

wood forests grow on intermittent ridges that provide an additional 1–1.5 m (3.3–4.9 ft) of elevation above the inundated wetland surface (Armentano et al. 2002). Similarly, the 237 islands in Florida Bay, which are made of marl, mangrove peat, siliceous sand, and limestone outcrops, are vegetated by tropical hardwood trees, mangroves, or algal flats separated by slight differences in elevation (Armentano et al. 2002).

Because the Everglades is naturally limited in phosphorus, the ocean provides the main source of nutrients for coastal plant growth (Childers et al. 2005, Davis et al. 2005, Castañeda-Moya et al. 2013). Seawater incursions during the dry season provide phosphorus to plants in the oligohaline marsh, and storm surges produced by tropical cyclones provide important intermittent pulses of nutrients (Castañeda-Moya et al. 2010, 2020). Mangrove productivity, basal area, and aboveground biomass increase toward the coast, likely due to increasing phosphorus availability near the ocean (Chen and Twilley 1999, Childers et al. 2005, Davis et al. 2005). In the Shark River

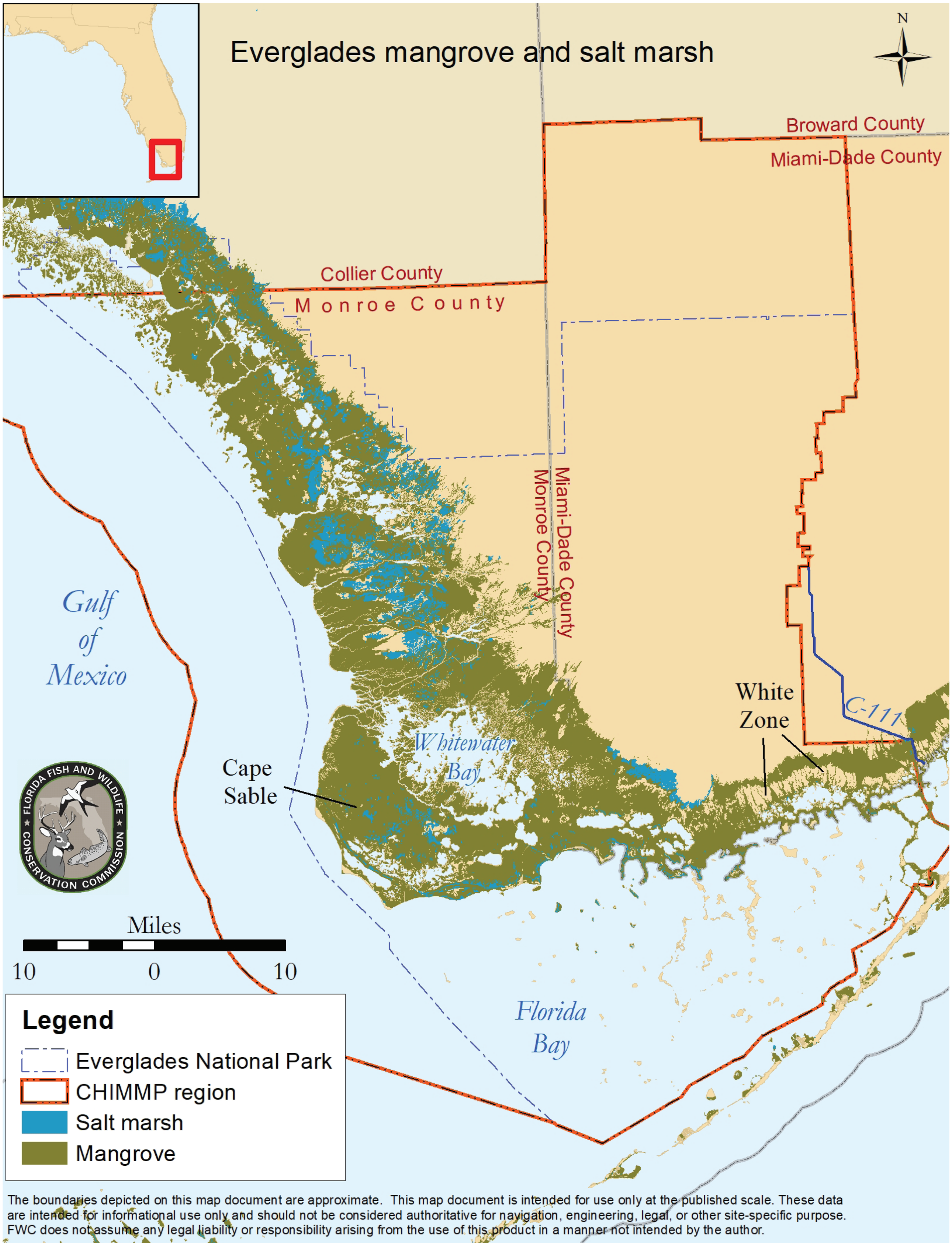

Figure 8.3. Salt marsh and mangrove extent in the Everglades. Data source: SFWMD 2014–2016 land-use/land-cover data, based on FLUCCS classifications (FDOT 1999, SFWMD 2018).

estuary, the high-nutrient mangrove forests along the coast are composed of mixed mangrove species dominated slightly by white mangroves (*Laguncularia racemosa*), while red mangroves (*Rhizophora mangle*) are predominant in the lower-nutrient forests 5–10 km (3–6 mi) upstream (Chen and Twilley 1999).

Hydrologic alterations

Massive hydrologic changes have drastically altered hydrologic conditions in the Everglades (Figure 8.2). Although hydrologic adjustments began in the late 1800s, the U.S. Army Corps of Engineers' Central and Southern Florida Project completed major changes to hydrology in the 1950s and 1960s. The goals of the Central and Southern Florida Project were to prevent floods and to drain lands for agriculture and development through construction of a series of levees, impoundments, pumps, and canals. Ultimately, these efforts resulted in the diversion of natural surface water into constructed channels that ushered water out to sea (Huber et al. 2007). The Herbert Hoover Dike prevented water from seeping over the southern edge of Lake Okeechobee. Instead, water was released through a network of canals to the east coast of Florida and to the Caloosahatchee River (Figure 8.2). The resulting drainage of land south of Lake Okeechobee enabled the development of the expansive Everglades Agricultural Area. Water continued to flow south from the Everglades Agricultural Area, and high-nutrient agricultural runoff resulted in the proliferation of cattails (*Typha* spp.) in the historically oligotrophic ecosystem (Chimney and Goforth 2001, Huber et al. 2007). The spread of agriculture and urbanization has reduced the natural area of the Everglades by 50%, and a large proportion of the remaining undeveloped area is reserved for water conservation (Figure 8.2; Chimney and Goforth 2001). The coastal Everglades has also been notably impacted by altered hydrology and reduced surface-water flow. One of the most noticeable differences is the expansion of mangrove swamps at the expense of salt marshes. This ecological shift is clearly visible in the comparison of vegetation extent between 1943 (Figure 8.4) and 2016 (Figure 8.3).

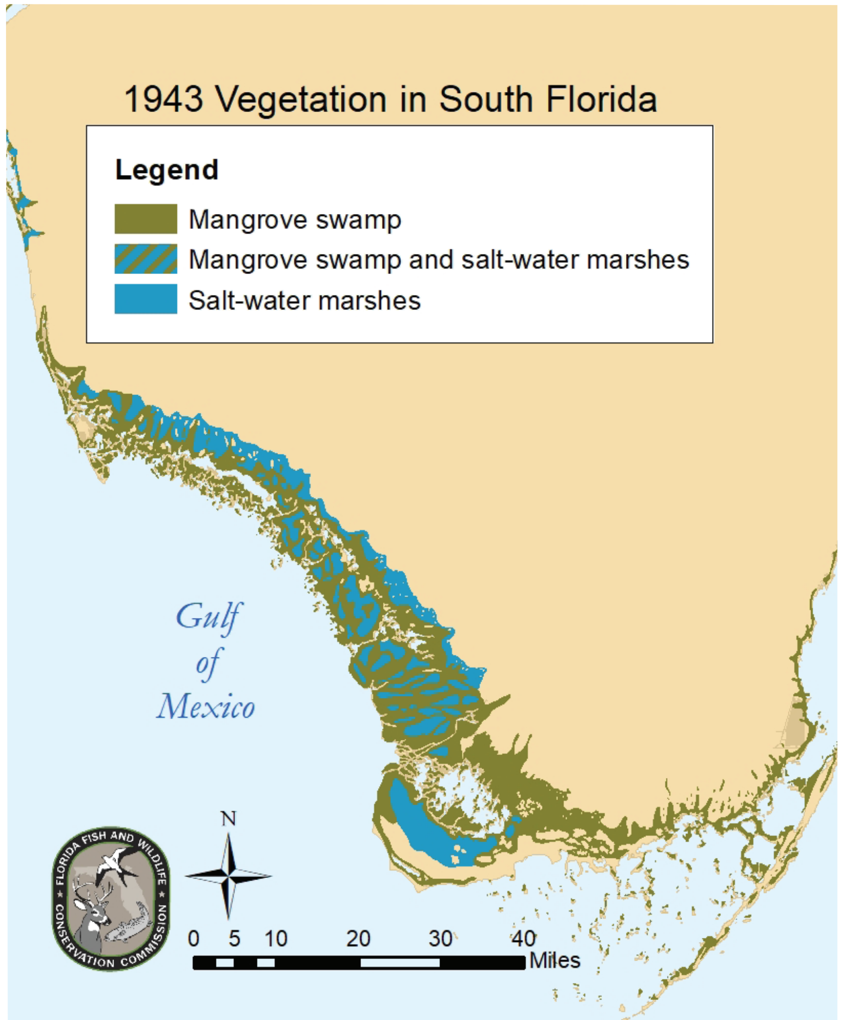

Figure 8.4. Extent of mangrove swamps and salt marshes in 1943, before the hydrologic changes of the Central and South Florida Project. Data source: Davis 1943.

Ecological disturbances due to human alterations of natural hydrology were first reported in the Everglades as early as 1938 (Chimney and Goforth 2001). Extensive drying of the Everglades resulted in soil loss via oxidation, fires, degradation of tree islands, invasion of nonnative species, and widespread changes in the Florida Bay ecosystem (McIvor et al. 1994, Chimney and Goforth 2001, Huber et al. 2007). Awareness of the extensive environmental damage caused by human activity has led current and planned endeavors focused on conservation and restoration (Chimney and Goforth 2001, Huber et al. 2007). In 2000, the Comprehensive Everglades Restoration Plan (CERP) was authorized to correct piecemeal attempts at water management in the Everglades during the previous 30 years (Perry 2004). Major CERP goals include improving water availability during the dry season and reducing flooding of urban and agricultural areas during the wet season (CERP 2015, 2019). While most of CERP has focused on water storage and nutrient removal, ecological management of Lake Okeechobee and increasing the freshwater sheet flow to the Everglades and adjacent estuaries are major goals that directly impact Everglades coastal wetlands (CERP 2015, 2019).

A large portion of the Everglades is encompassed by Everglades National Park, including most of the coastal Everglades in Monroe County. Although authorized by Congress in 1934, Everglades National Park was not officially established until 1947 (USNPS 1979). In the 1970s and 1980s, Everglades National Park was recognized as a Biosphere Reserve, UNESCO World Heritage Site, and Wetland of International Importance; it is one of only three sites in the world to have been placed on all three lists (USFWS 1999). Coastal wetlands in the northwestern Everglades (Collier County) are included in the boundaries of the Ten Thousand Islands National Wildlife Refuge and a network of Florida's Aquatic Preserves (see Chapter 7).

Unique ecosystems

Several regions in and around the Everglades have unique ecosystems as a result of their hydrology and location. These regions include Florida Bay, Cape Sable, and the Southeast Saline Everglades.

- **Florida Bay:** A broad, shallow bay south of the Everglades, Florida Bay was historically characterized by clear waters and extensive seagrass beds. Today, Taylor Slough and the C-111 canal are the primary freshwater sources for Florida Bay (Figures 8.2 and 8.3). Freshwater input is much less than historical levels (Smith et al. 1989), and models reveal that salinity is higher in the euryhaline marshes bordering Florida Bay than it was before human development (Marshall et al. 2009). While historical average salinity in Florida Bay is estimated to have ranged from 3 to 30 on the practical salinity scale (Marshall et al. 2009), from 1998 through 2004 the average salinity ranged from 23 to 39 (Kelble et al. 2007). In the late 1980s and early 1990s, large-scale ecological regime shifts toward hypersaline waters, hypoxia, increased heat stress, and decreased water clarity resulted in widespread algal blooms and mortality of mangroves, seagrass beds, sponges, lobsters, and shrimp (McIvor et al. 1994, Fourqurean and Robblee 1999). A similar Florida Bay seagrass mortality event in 2015 has also been linked to hypersalinity, stratification, and anoxia (Hall et al. 2016, CERP 2019). In 2016, a plan was adopted as part of CERP to mitigate the impact of droughts by increasing freshwater input to Florida Bay (CERP 2019).

  While inland mangrove expansion is common throughout Florida, mangroves on islands in Florida Bay have been noted to expand both inland and into adjacent shallow waters (Zhai et al. 2019). The area of these islands increased between 1984 and 2012 as a result of outward mangrove expansion during a time when relative sea level was also rising. Following Hurricane Irma, however, the extent and elevation of mangrove berms on many islands in Florida Bay declined (Wingard et al. 2020).

- **Cape Sable:** Cape Sable (Figure 8.3) is the area of the Everglades least affected by urbanization and mainland hydrologic alterations because it is separated from the Florida mainland by Whitewater Bay (Wanless and Vlaswinkel 2005, Wingard and Lorenz 2013). Cape Sable includes extensive mangrove forests, many of which are dwarf mangroves (Zhang 2011, Wingard and Lorenz 2013). The region has not entirely escaped modification; in the 1920s, ditches were dug through coastal berms to connect the interior lakes, which enabled saltwater intrusion (Wanless and Vlaswinkel 2005). Increased tidal current strength due to sea-level rise has caused coastal erosion, redistributed sediment, created new tidal creeks, and increased tidal reach. As a result of saltwater inundation, the underlying peat in the formerly freshwater marshes is decaying, further lowering substrate elevations on the interior of the cape (Wanless and Vlaswinkel 2005). Forested wetlands surrounding lagoons in and around Cape Sable experienced significant damage after Hurricane Irma (Zhang et al. 2019), with many areas showing minimal recovery 15 months after the storm (Lagomasino et al. 2020).

- **The Southeast Saline Everglades (the white zone):** The land northeast of Florida Bay is known as the Southeast Saline Everglades (Egler 1952, Ross et al. 2000). Before development and hydrologic alterations in South Florida, mangrove shrubs grew on the coast in a thin band that gradually transitioned to a sparse mangrove–graminoid marsh, and sawgrass dominated freshwater marshes several kilometers inland (Ross et al. 2002). Restricted freshwater flow and highly variable soil salinity constrain plant growth in this region. From an aerial view, most of the Southeast Saline Everglades appears white due to the low vegetative cover and the highly reflective nature of the marl substrate; hence, the area is often referred to as the white zone (Figure 8.3; Ross et al. 2000, Browder et al. 2005, Briceño et

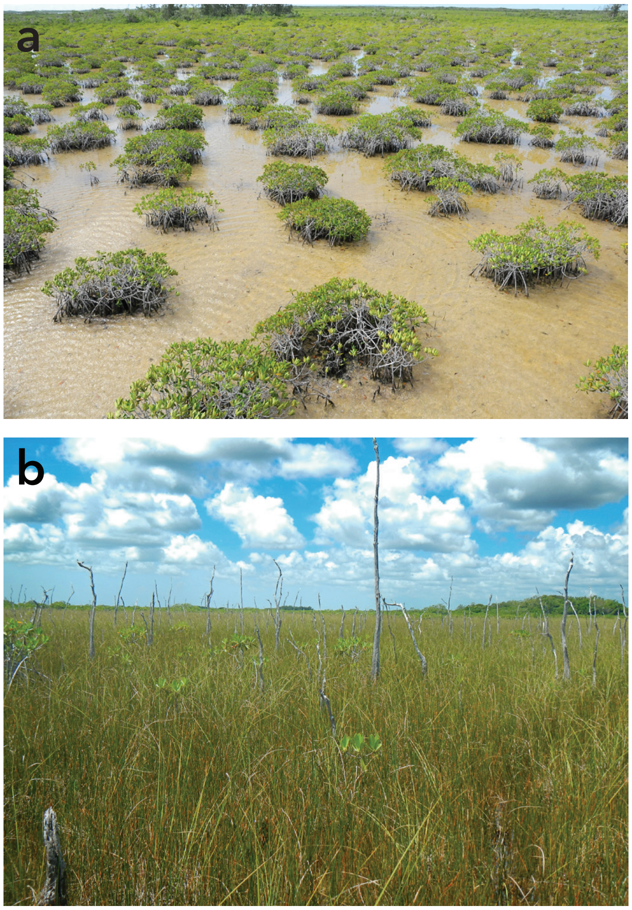

Figure 8.5. The Southeast Saline Everglades (the white zone), is an ecotone characterized by widely spaced dwarf or scrub mangrove trees and large expanses of shallow open water (a). Hurricane Betsy resulted in the presence of dead cypress (*Taxodium* spp.) in the inland Southeast Saline Everglades (b). Note the red mangrove (*Rhizophora mangle*) seedlings within the mixed marsh of sawgrass (*Cladium jamaicense*) and Gulf coast spikerush (*Eleocharis cellulosa*). Photo credits: South Florida/Caribbean Network staff.

al. 2011). The vegetation in the white zone consists of dwarf or scrub mangroves, with few grasses (Figure 8.5a). The mangroves are generally not tall or dense enough to be categorized as mangrove forest under most land-cover classification systems. Between 1940 and 1994, the white zone expanded inland by approximately 1.5 km (0.9 mi) as a result of reduced surface freshwater flow and sea-level rise (Ross et al. 2000). The edge of the white zone shifted least at sites where surface freshwater flow was not restricted by roads or levees, demonstrating that freshwater flow can lessen the landward transgression of the white zone (Ross et al. 2000). Though freshwater flow can mitigate encroachment of the white zone and saltwater intrusion, sea-level rise is the primary cause of saltwater encroachment (Meeder et al. 2017).

Impact of tropical storms and hurricanes

Tropical storms and hurricanes continually shape South Florida coastal wetlands. The 1935 Category 5 Labor Day hurricane caused extensive mortality to the coastal mangrove forest. The great girth and height of South Florida mangroves before the hurricane indicated that the region had likely not suffered such a severe storm for many decades (Craighead and Gilbert 1962, Armentano et al. 2002). In some areas, the 1935 hurricane induced an ecological regime shift from mangrove to intertidal mudflats which have remained unvegetated even 85 years later (Smith et al. 2009, Osland et al. 2020). Hurricane Donna in 1960 severely damaged the mangrove belt between Flamingo and Lostman's River; with few exceptions all mangrove trees greater than 5 cm (2 in.) in diameter were sheared off at 2–3 m (6–10 ft) above the ground (Craighead and Gilbert 1962). In 1965, Hurricane Betsy crossed the southern tip of Florida with winds of 160 to 225 km hr^{-1} (100 to 140 mph; ESSA 1965). A tidal surge increased soil chloride levels to as high as 19,000 ppm, and chloride levels remained elevated for several months (Alexander 1967). While many trees died as a direct result of wind damage, the elevated soil chloride levels had the greatest impact on the vegetation of the region, particularly in the marsh. Extensive areas of sawgrass were killed and were quickly replaced by Gulf coast spikerush (*Eleocharis cellulosa*) (Alexander 1967). The effects of Hurricane Betsy are still evident in the landscape, with dead cypress (*Taxodium* spp.) snags a common sight in the landscape (Figure 8.5b).

In 1992, Hurricane Andrew passed over the Everglades, destroying more than 28,000 ha (70,000 ac) of mangroves and causing extensive defoliation (Wanless et al. 1994, Armentano et al. 2002). Near the coastline, more than 90% of trees were uprooted or snapped (Smith et al. 1994, Wanless et al. 1994). Many buttonwood (*Conocarpus erectus*) forests were converted to mangrove swamps or halophytic prairie due to the saltwater inundation and substrate changes (Armentano et al. 2002). The abundance of palms and hardwoods in the coastal Everglades has also declined due to transition into mangrove swamps and salt flats.

Hurricane Wilma made landfall north of Everglades National Park in October 2005 as a Category 3 hurricane with maximum sustained winds of approximately 195 km hr^{-1} (121 mph; Pasch et al. 2006). A 5-m (16.4 ft) storm surge occurred on the Harney River (Soderqvist and By-

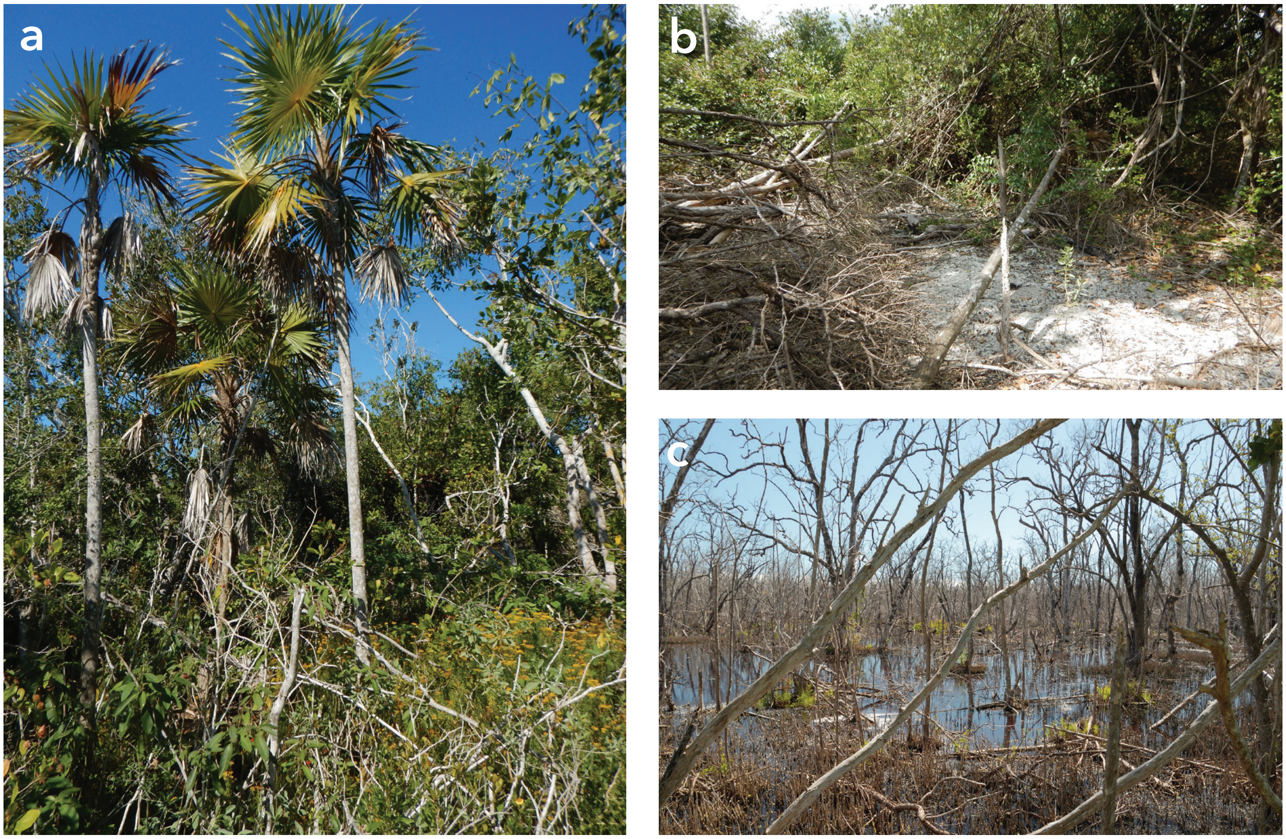

Figure 8.6. Mangrove and upland damage and partial recovery following Hurricane Irma in Everglades National Park on the north shoreline of Little Madeira Bay in March 2019 (a, b) and north of Christian Point Trailhead in October 2018 (c). Photo credits: Kevin Whelan (a, b) and Pablo Ruiz (c).

rne 2007). Smith et al. (2009) estimated 1,250 ha (3,090 ac) of mangroves were severely damaged by Hurricane Wilma in a 50-km (30 mi) band adjacent to the Gulf of Mexico.

Most recently, Hurricane Irma made landfall north of Everglades National Park near Marco Island as a Category 3 hurricane in September 2017. Maximum sustained wind speeds were 179 km hr^{-1} (112 mph) with gusts up to 207 km hr^{-1} (129 mph; Cangialosi et al. 2018). Storm surge water levels reached at least 1.8 m (6 ft) above ground level in the Everglades National Park (Cangialosi et al. 2018). The storm surge and high winds from Hurricane Irma caused widespread damage to the coastal Everglades (Figure 8.6; Taillie et al. 2019, Zhang et al. 2019). The extent of closed-canopy forest was reduced by 86%, which caused a 15% reduction in mangrove canopy volume in the months after the storm (Lagomasino et al. 2020). Mangroves taller than 10 m sustained the greatest amount of wind damage, but many recovered in the year after the storm. The storm surge from Hurricane Irma deposited a layer of marine-origin carbonate mud (Wingard et al. 2020) and flooded mangrove basin forests for prolonged periods (Lagomasino et al. 2020). Areas with thick storm surge deposits or prolonged flooding had high mangrove mortality (Radabaugh et al. 2020). Black mangrove basin forests were most vulnerable to Hurricane Irma, comprising over two-thirds of the area of mangrove mortality (Lagomasino et al. 2020).

Threats to coastal wetlands

- **Hydrologic alteration:** Although the coastal wetlands in Everglades National Park are protected from direct impacts of urbanization, they are highly vulnerable to hydrologic changes and natural disturbances. According to hydrologic models, water levels in the major sloughs of the Everglades are 0.15 m (0.5 ft) lower than historical levels; likewise, freshwater delivery to coastal wetlands and estuaries is 2.5–4 times less than predrainage volume (Marshall et al. 2009). The relationship between freshwater levels in Everglades National Park and sea level along the coast is critical in understanding the encroachment of seawater and nutrients into historically freshwater regions. The even distribution of freshwater inflow throughout the year is more effective at reducing saltwater intrusion than high annual volumes as freshwater input is particularly important during the dry season (Dessu et al. 2018). Additionally, freshwater flow decreases water residence time in the sloughs, flushing out salt and nutrients (Sandoval et al. 2016). Many tidal creeks along the lower Everglades have been filled in by vegetation and sediment as a result of low freshwater flow and nutrients provided by rising sea levels (Davis et al. 2005). Choked waterways and reduced flushing are detrimental to wetlands as flushing is important for the resiliency and long-term viability of wetlands (Davis et al. 2005, Wanless and Vlaswinkel 2005).

- **Climate change and sea-level rise:** The impact of reduced freshwater flow is exacerbated by saltwater intrusion due to storm surges and sea-level rise. Saltwater intrusion has already extended into formerly oligohaline and freshwater marshes in the coastal Everglades, and mangrove extent has expanded inland (Ross et al. 2000, Davis et al. 2005, Smith et al. 2013). Groundwater resources are also at risk of being contaminated by salt water (Wanless et al. 1994). Models indicate that inundation due to sea-level rise will be gradual at first but then will accelerate in some regions due to topography (Zhang 2011). Much of South Florida is a natural depression with moderate elevation, so inundation progresses rapidly once sea level reaches a threshold (1.25 m/4.1 ft is the threshold in Miami-Dade County; Zhang 2011). If natural barriers such as the Atlantic Coastal Ridge or the Big Cypress Swamp Ridge are breached, saltwater inundation would flood large portions of the Everglades (Wanless et al. 1994). Even a conservatively estimated sea-level rise of 0.5 m (1.6 ft) would inundate much of Everglades National Park (Zhang 2011).

  If peat accumulation cannot keep pace with sea-level rise, coastal mangroves will not be able to maintain their present locations and the shoreline will erode (Davis et al. 2005). Increased wave activity would increase erosion and exposure of mangrove peat, making the organic matter more vulnerable to oxidation. Oxidation may be avoided if storm surge transports such organic carbon inland and reburies it as new deposits (Smoak et al. 2013). Recent research has found that the rate of carbon burial has increased over the past 100 years in southwest Florida mangroves (Breithaupt et al. 2020b), and forest elevation is being increased further by hurricane deposits (Whelan et al. 2009, Smith et al. 2009, Castañeda-Moya et al. 2010, Feher et al. 2019). Storm-surge deposits also stand to enhance preservation of peat by providing a covering that reduces oxidation (Breithaupt et al. 2020a).

- **Storm events:** The strong winds and storm surge from hurricanes and tropical storms shape the structure of mangrove forests by snapping trunks, uprooting trees, defoliating the canopy, and leaving a deposit of marine-origin mud on the forest floor. While many forests can rebound in the months after a storm, delayed mortality caused by storm-surge deposits and prolonged flooding can delay recovery in low-lying areas and interior basins (Lagomasino et al. 2020, Radabaugh et al. 2020). Hurricane-induced mangrove mortality and subsequent oxidation and peat collapse have been linked with elevation loss and the conversion of mangrove forests to mud flats in southwest Florida (Smith et al. 2009, Osland et al. 2020). Ensemble climate models continue to project that the number of tropical cyclones in the North Atlantic will decrease under future warming scenarios (IPCC 2014), as will the number of tropical cyclones that make landfall in the United States (Stansfield et al. 2020). The same models project, however, that the average intensity of these storms will increase, resulting in higher wind speeds and greater rainfall intensities (Stansfield et al. 2020). Thus, despite a decrease in the number of storms, greater damage and longer-lasting impacts to coastal wetlands in Florida remain likely and will probably increase as land-falling storms grow more intense.

- **Invasive vegetation:** As in much of Florida, invasive plants, such as Brazilian pepper (*Schinus terebinthifolia*), latherleaf (*Colubrina asiatica*), Old World climbing fern (*Lygodium microphyllum*), and melaleuca (*Melaleuca quinquenervia*) continue to expand their extent and outcompete native plants on the edges of coastal wetlands in southern Florida (USFWS 1999, Davis et al. 2005, Wingard and Lorenz 2013). For example, Brazilian pepper in the interior marshes and shrublands of the coastal Everglades occupies about 12,000 ha (30,000 ac; Figure 8.7). When present, its infestation density is generally less than 50%, but monotypic stands can have an infestation density of more than 89% (Figure 8.7). Invasive vegetation is particularly threatening after a disturbance, as it can outpace the regrowth of native vegetation.

Mapping and monitoring efforts

Water management district mapping

The South Florida Water Management District (SFWMD) conducts regular land-use/land-cover (LULC) surveys every 3–5 years in the district. Figure 8.3 shows the 2014–2016 LULC map, the most recent SFWMD LULC

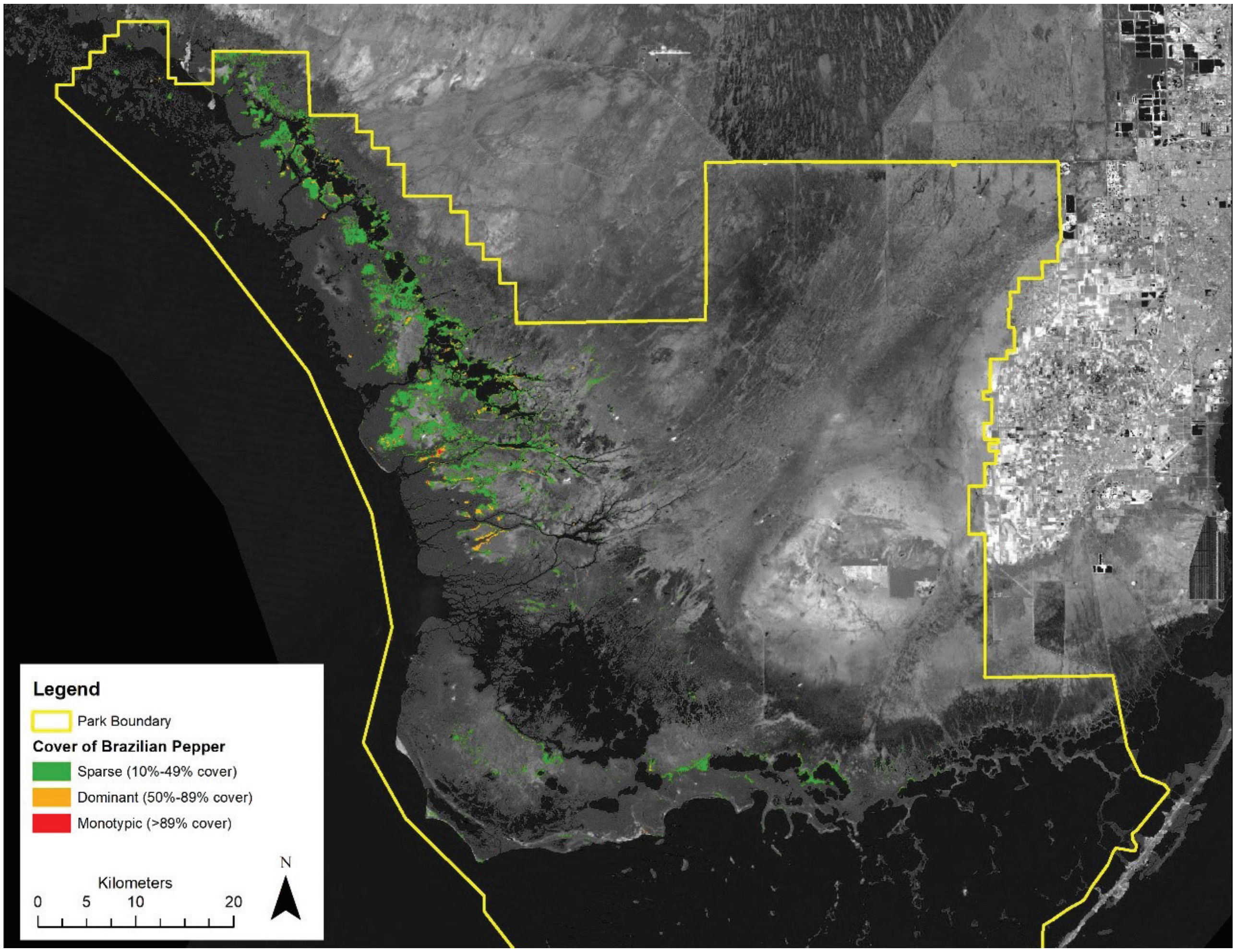

Figure 8.7. Distribution and density of Brazilian pepper (*Schinus terebinthifolia*) at the mangrove–freshwater marsh ecotone in southern Florida, Everglades National Park. Data compiled from Ruiz et al. 2017, 2018, 2020.

map of the Everglades available at publication. Land-cover classifications are based on an SFWMD-modified Florida Land Use and Cover Classification System (FLUCCS) (FDOT 1999, SFWMD 2009). Minimum mapping units were 2 ha (5 ac) for uplands and 0.2 ha (0.5 ac) for wetlands. The 2014–2016 LULC maps were made by interpreting aerial photography and updating 2008–2009 vector data.

Comprehensive Everglades Restoration Plan monitoring

Project reports, monitoring information, and feasibility studies produced under CERP are available from the CERP website https://www.evergladesrestoration.gov/, including the 2019 System Status Report (CERP 2019).

Long-term Ecological Research mapping and monitoring

The National Science Foundation's Long-term Ecological Research (LTER) network includes a section in the Florida Coastal Everglades. This program, based at Florida International University, was established in 2000 and involves the collaboration of many governmental, academic, and independent organizations. A variety of vegetation, land-cover, and mangrove biomass maps are available from the Florida Coastal Everglades LTER website (https://fce-lter.fiu.edu/data/GIS/).

National Park Service's South Florida/Caribbean Network mapping

The South Florida/Caribbean Network, the U.S. Army Corps of Engineers, and the SFWMD are collaborating to create vegetation maps of Everglades National Park and Big Cypress National Preserve. This project covers an area of 7,400 km^2 (2,900 mi^2) and provides information on pre-CERP baseline reference conditions, documenting the spatial extent and pattern of vegetation communities as they were before CERP was implemented. This mapping has species-level vegetation characterization at a spatial resolution of 0.25 ha (0.6 ac; Ruiz et al. 2017). The project includes four mapping regions in Everglades National Park (regions 1–4) and three in Big Cypress National Preserve (regions 5–7). Detailed vegetation maps are available for the Southeast Saline Everglades (region 2; Ruiz et al. 2017), Southwest Coastal Everglades (region 3; Ruiz et al. 2018), Eastern Big Cypress (regions 5 and 6; Ruiz et al. 2019), the Northwest Coastal Everglades (region 4; Ruiz et al. 2020), and Western Big Cypress (region 7; Whelan et al. 2020). The report for Shark River Slough/Long Pine Key is available (region 1; Schall et al. 2020), and the map will be made available when completed from https://irma.nps.gov/DataStore/.

Mangrove-marsh ecotone mapping and monitoring

- Smith et al. (2013) created detailed maps documenting changes in mangrove swamp and marsh extent in three locations in the Everglades from 1928 through 2004. In two of the three sites, the area of mangrove forests expanded, and marsh area declined. This expansion in mangrove forest has been attributed to sea-level rise. Fires did not prevent landward mangrove expansion and may have assisted mangrove encroachment into some marshes.
- Han et al. (2018) used remote-sensing data to map changes in mangrove extent in Everglades National Park from 1985 to 2017. The study found that hurricane damage changed the spectral signature of the mangroves; thus, a smaller mangrove area was mapped in years following major storms. Within 3–4 years, enough canopy recovered to restore the spectral signature of mangrove forests and their mapped coverage. Mangrove extent in the outer coastal zone generally decreased, but these losses were exceeded by the inland expansion of mangroves into marshes.
- The National Park Service has established an ecotone monitoring program to track the transition from mangrove forest to marsh (Moser et al. 2019). Aerial imagery is being used to delineate the location of the mangrove ecotonal boundary at fourteen 3-km (1.9 mi) segments that are systematically located along the inland mangrove boundaries in Everglades National Park and Big Cypress National Preserve. Every third 3-km segment is digitized and ground-truthed at four locations along the segment. Ground truthing includes documentation of species composition, percent cover, and canopy height of herbaceous and forest vegetation. The pilot project was completed in 2010–2011. Monitoring will be repeated approximately every 10 years (Moser et al. 2019).

Everglades vegetation model

Everglades Landscape Vegetation Succession (ELVeS) is an open-source model written in Java that simulates changes in vegetation in response to varying abiotic conditions. Led by the South Florida Natural Resources Center of Everglades National Park, this modeling effort is based on vegetation niches, replacement probabilities, and time lags for transition periods. The model is available for download and use from https://www.jem.gov/Modeling/GetView/ELVeS.

Mangrove height mapping

In 2006, mangrove height was mapped in Everglades National Park using data from the National Aeronautics and Space Administration's (NASA) Shuttle Radar Topography Mission (Simard et al. 2006). These data were calibrated with airborne light detection and ranging (LiDAR) data and a U.S. Geological Survey (USGS) digital elevation model. Field data were then used to extrapolate mangrove biomass from tree height. Average tree height was found to be around 8 m (26 ft).

Mangrove canopy height was remapped with interferometric synthetic aperture radar (In-SAR) data from the German Space Agency's TanDEM-X twinned satellite constellation (Feliciano et al. 2017). This study found mangrove growth and expansion into new regions caused an increase in mangrove stature and biomass. More recently, a 1-m (3.3 ft) resolution mangrove canopy height map was created using stereo imagery collected by commercial satellite, WorldView-2, through the NextView License Agreement (Neigh et al. 2013; Lagomasino et al. 2020). The high-resolution mangrove canopy height information was used to model wind damage after Hurricane Irma. Mangrove forests lost an average of 1.16 m (3.8 ft) of canopy height and canopy volume decreased by 15% (Lagomasino et al. 2020).

NASA G-LiHT mapping

Remote-sensing monitoring of coastal areas in southwest Florida was conducted by NASA Goddard's LiDAR,

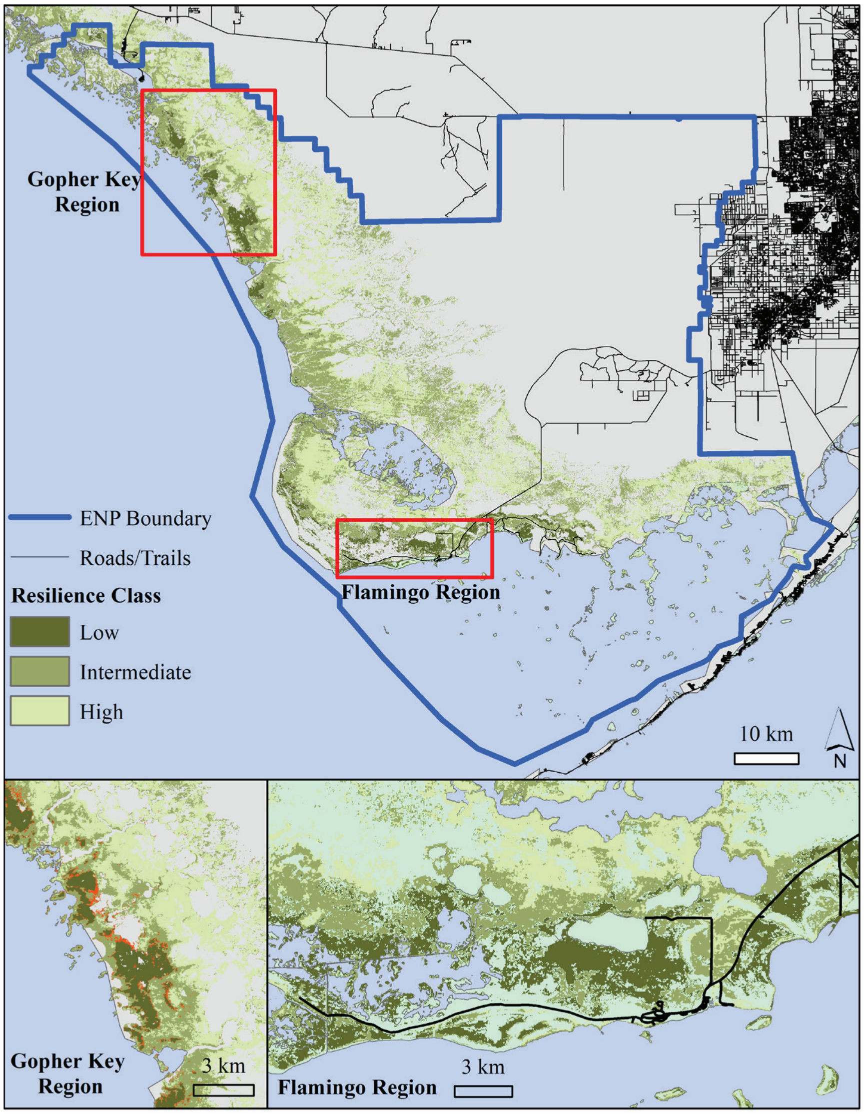

Figure 8.8. Resilience of mangrove forests in Everglades National Park, as assessed 15 months following Hurricane Irma, which made landfall in September 2017. High-resilience forests are expected to recover in 5 years, intermediate-resilience forests in 5–15 years, and low-resilience forests in >15 years (Lagomasino et al. 2020).

veys (White et al. 2013), but because data acquisitions coincided with Hurricane Irma, researchers were able to use data from the flight campaigns in South Florida to estimate Irma's damage to mangrove forests (Lagomasino et al. 2017, 2018, Chavez et al. 2019, Taillie et al. 2020) and to forecast damage under extreme cyclone scenarios (Zhang et al. 2019). The LiDAR data from G-LiHT surveys and high-resolution aerial photos were combined with satellite observations to estimate that 332 km^2 (128 mi^2) of mangrove forests across South Florida were severely damaged (Zhang et al. 2019). Recent reports include multiple satellite observations between December 2017 and December 2018 which enabled estimation of the extent of mortality and the change in mangrove forest composition caused by delayed mortality from extended ponding (Lagomasino et al. 2020). Resilience of the mangrove forests was classified based on post-Irma decline and recovery of the normalized difference vegetation index (NDVI). Many of the mangrove forests within 10 km (6 mi) of the coast, particularly black mangrove basin forests, were found to have low or intermediate resilience following the hurricane (Figure 8.8; Lagomasino et al. 2020).

Hyperspectral and Thermal (G-LiHT) airborne imager (Cook et al. 2013, https://gliht.gsfc.nasa.gov/). The airborne instrument makes coincident measurements from each of five sensors, providing a unique view of the landscape that a single sensor could not provide. Pre-Irma (March 2017) and post-Irma (November–December 2017 and March 2020) aerial photographs and LiDAR data were collected by G-LiHT over much of southwest Florida. Approximately 130,000 ha (320,000 ac) of wetlands were covered by the G-LiHT campaign, with the majority collected over Everglades National Park. This instrument has been used primarily to augment forest inventory sur-

Recommendations for protection, management, and monitoring

- Continue efforts to improve the quantity, quality, timing, and distribution of freshwater input to maintain estuarine conditions in the coastal Everglades and Florida Bay. Realistic projections of future sea-level rise, including worst-case scenarios, should be taken into account when assessing the increasing freshwater needs of Everglades mangroves and salt marshes. Coastal wetland vegetation that is chronically stressed due to altered hydrology may prove less resilient following a disturbance such as a hurricane or drought (Krauss et al. 2018).

- Continue mapping and monitoring mangrove forests heavily impacted by Hurricane Irma to determine the characteristics of forests that successfully recover, experience changes in species composition, or become tidal flats following hurricane damage (Smith et al. 2009, Feher et al. 2019, Lagomasino et al. 2020, Osland et al. 2020, Radabaugh et al. 2020). Systematic, long-term monitoring also provides baseline data for ecosystem conditions that will aid in evaluating future disturbances.
- Monitor vegetation and water quality to identify stressed areas, evaluate the success of restoration projects, and predict impacts of future restoration actions. Interagency cooperation in the restoration of mangrove forests along Florida's southwest coast may also lead to valuable insights that can be shared with other regions of Florida and other countries in the global effort to maintain and regain coastal mangrove forests.
- Monitor coastal ecosystems in Cape Sable, Florida Bay, and the Southeast Saline Everglades, as these sites may serve as sentinel indicators for the impacts of rising sea level, providing information for adaptive management and decision-making (Wanless and Vlaswinkel 2005).
- Conduct standardized monitoring to identify the spread of invasive plant species and evaluate the effectiveness of removal efforts. Active restoration, including the planting of native species, could further increase the success of combating invasive vegetation in high-priority areas.

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Works cited

Alexander TR. 1967. Effect of Hurricane Betsy on the southeastern Everglades. Q J Fla Acad Sci. 39:10–24.

Armentano TV, Jones DT, Ross MS, Gamble BW. 2002. Vegetation pattern and process in tree islands of the southern Everglades and adjacent areas. In: Sklar F, van der Valk A, editors. Tree islands of the Everglades. Boston, MA: Kluwer Academic Publishers. p. 225–281.

Breithaupt JL, Hurst N, Steinmuller HE, Duga E, et al. 2020a. Comparing the biogeochemistry of storm surge sediments and pre-storm soils in coastal wetlands: Hurricane Irma and the Florida Everglades. Estuaries Coast. Special issue: Impact of 2017 Hurricanes. 43:1090–1103.

Breithaupt JL, Smoak JM, Bianchi TS, Vaughn D, et al. 2020b. Increasing rates of carbon burial in southwest Florida coastal wetlands. J Geophys Res Biogeosci. 125(2). https://doi.org/10.1029/2019JG005349.

Briceño HO, Boyer JN, Harlem P. 2011. Ecological impacts on Biscayne Bay and Biscayne National Park from proposed south Miami-Dade County development, and derivation of numeric nutrient criteria for south Florida estuaries and coastal waters. Miami, FL: Florida International University–Southeast Environmental Research Center. Available from http://serc.fiu.edu/wqmnetwork/BNP/Final%20Report%20BNP.pdf.

Browder JA, Alleman R, Markely S, Ortner P, Pitts PA. 2005. Biscayne Bay conceptual ecological model. Wetlands. 25:854–869.

Cangialosi JP, Latto AS, Berg R. 2018. National Hurricane Center tropical cyclone report. Hurricane Irma (AL 112017) 30 August–12 September 2017. Tropical Cyclone Report. Miami, FL: National Hurricane Center. Available from https://www.nhc.noaa.gov/data/tcr/AL112017_Irma.pdf.

Castañeda-Moya E, Rivera-Monroy VH, Chambers RM, Zhao X, et al. 2020. Hurricanes fertilize mangrove forests in the Gulf of Mexico (Florida Everglades, USA). Proc Natl Acad Sci USA. 117:4831–4841.

Castañeda-Moya E, Twilley RR, Rivera-Monroy VH. 2013. Allocation of biomass and net primary productivity of mangrove forests along environmental gradients in the Florida Coastal Everglades, USA. For Ecol Manage. 307:226–241.

Castañeda-Moya E, Twilley RR, Rivera-Monroy VH, Zhang K, et al. 2010. Sediment and nutrient deposition associated with Hurricane Wilma in mangroves of the Florida coastal Everglades. Estuaries Coast. 33:45–58.

CERP (Comprehensive Everglades Restoration Program). 2015. Central & southern Florida project report to Congress: Comprehensive Everglades Restoration Plan. Available from https://evergladesrestoration.gov/content/cerpreports/cerp_2015_rpt_to_congress.pdf.

CERP (Comprehensive Everglades Restoration Program). 2019. 2019 system status report. U.S. National Park Service, South Florida Water Management District, U.S. Army Corps of Engineers, and U.S. Fish and Wildlife Service. https://www.saj.usace.army.mil/Missions/Environmental/Ecosystem-Restoration/RECOVER/2019-System-Status-Report/, accessed June 2020.

Chavez S, Wdowinski S, Lagomasino D, Fatoyinbo T, et al. 2019. Observing changes in the mangrove forests of the south Florida Everglades following Hurricane Irma using remote sensing measurements. Abstracts, AGU Fall Meeting, San Francisco, CA, December 9–13, 2019. Washington, DC: American Geophysical Union. https://agu.confex.com/agu/fm19/meetingapp.cgi/Paper/616936, accessed January 2020.

Chen R, Twilley RR. 1999. Patterns of mangrove forest structure and soil nutrient dynamics along the Shark River Estuary, Florida. Estuaries. 22:955–970.

Childers DL, Boyer JN, Davis SE III, Madden CJ, et al. 2005. Nutrient concentration patterns in the oligotrophic "upside-down" estuaries of the Florida Everglades. Limnol Oceanogr. 51:602–616.

Chimney MJ, Goforth G. 2001. Environmental impacts to the Everglades ecosystem: a historical perspective and restoration strategies. Water Sci Technol. 44:93–100.

Cook BD, Corp IA, Nelson RF, Middleton EM, et al. 2013. NASA Goddard's LiDAR, Hyperspectral and thermal (G-LiHT) airborne imager. Remote Sens. 5:4045–4066.

Craighead FC, Gilbert T. 1962. The effects of Hurricane Donna on the vegetation of southern Florida. Q J Fla Acad Sci. 25:1–28.

Davis JH Jr. 1943. Vegetation map of southern Florida. Figure 71 in: The natural features of southern Florida, especially the vegetation, and the Everglades. Florida Geological Survey Bulletin. 25. https://ufdc.ufl.edu/UF00015184/00001, accessed June 2020.

Davis SM, Childers DL, Lorenz JJ, Wanless HR, Hopkins, TE. 2005. A conceptual model of ecological interactions in the mangrove estuaries of the Florida Everglades. Wetlands. 25:832–842.

Dessu SB, Price RM, Troxler TG, Kominoski JS. 2018. Effects of sea-level rise and freshwater management on long-term water levels and water quality in the Florida coastal Everglades. J Environ Manage. 211:164–176.

Egler FE. 1952. Southeast Saline Everglades vegetation, Florida, and its management. Vegetatio Acta Geobotanica. 3:213–265.

ESSA (Environmental Science Services Administration). 1965. Hurricane Betsy August 27–September 12, 1965 preliminary report with advisories and bulletins issued. Washington, DC: U.S. Department of Commerce, ESSA Weather Bureau. https://www.nhc.noaa.gov/archive/storm_wallets/atlantic/atl1965/betsy/prenhc/, accessed August 2020.

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

Feher LC, Osland MJ, Anderson GH, Vervaeke WC, et al. 2019. The long-term effects of hurricanes Wilma and Irma on soil elevation change in Everglades mangrove forests. Ecosystems. 27:1–5.

Feliciano EA, Wdowinski S, Potts MD, Lee SK, Fatoyinbo TE. 2017. Estimating mangrove canopy height and above-ground biomass in the Everglades National Park with airborne LiDAR and TanDEM-X data. Remote Sens. 9(7):702.

Fourqurean JW, Robblee MB. 1999. Florida Bay: a history of recent ecological changes. Estuaries. 22:345–357.

Hall MO, Furman BT, Merello M, Durako MJ. 2016. Recurrence of *Thalassia testudinum* seagrass die-off in Florida Bay, USA: initial observations. Mar Ecol Prog Ser. 560:243–249.

Han X, Feng L, Hu C, Kramer P. 2018. Hurricane induced changes in the Everglades National Park mangrove forest: Landsat observations between 1985 and 2017. J Geophys Res Biogeosci. 123(11):3470–3488.

Huber WC, Bedford BL, Blum IK, Boesch DF, et al. 2007. Progress toward restoring the Everglades: the first biennial review, 2006. Washington, DC: The National Academies Press. https://www.nap.edu/catalog/11754/progress-toward-restoring-the-everglades-the-first-biennial-review-2006, accessed April 2020.

IPCC (Intergovernmental Panel on Climate Change). 2014. Climate change 2014: synthesis report. Contribution of working groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Pachauri RK, Meyer LA, editors. Geneva, Switzerland. IPCC. Available from https://www.ipcc.ch/site/assets/uploads/2018/05/SYR_AR5_FINAL_full_wcover.pdf.

Kelble CR, Johns EM, Nuttle WK, Lee TN, et al. 2007. Salinity patterns in Florida Bay. Estuar Coast Shelf Sci. 71:318–334.

Krauss KW, Demopoulos AW, Cormier N, From AS, et al. 2018. Ghost forests of Marco Island: mangrove mortality driven by belowground soil structural shifts during tidal hydrologic alteration. Estuar Coast Shelf Sci. 212:51–62.

Lagomasino D, Cook B, Fatoyinbo T, Morton DC, et al. 2017. Using high-resolution imagery to characterize disturbance from Hurricane Irma in South Florida wetlands. In: Abstracts. AGU Fall Meeting, New Orleans, LA, December 11–15, 2017. Washington, DC: American Geophysical Union. https://ui.adsabs.harvard.edu/abs/2017AGUFMNH23E2880L/abstract, accessed January 2020.

Lagomasino D, Fatoyinbo T, Castañeda-Moya E, Cook B, et al. 2020. Storm surge, not wind, caused mangrove dieback in southwest Florida following Hurricane Irma. In review, Nat Commun. https://doi.org/10.31223/osf.io/q4exh

Lagomasino D, Fatoyinbo T, Morton DC, Cook B, et al. 2018. Heterogeneous patterns of mangrove disturbance and recovery from Hurricane Irma. In: Abstracts. AGU Fall Meeting, Washington, DC, December 10–14, 2018. Washington, DC: American Geophysical Union. https://ui.adsabs.harvard.edu/abs/2018AGUFM.B41F2775L/abstract, accessed January 2020.

Lagomasino D, Fatoyinbo T, Payton A, Taillie PJ, et al. 2019. Hurricane-related forest degradation and dieback across the Caribbean. In: Abstracts. AGU Fall Meeting, San Francisco, CA, December 9–13, 2019. Washington, DC: American Geophysical Union. https://agu.confex.com/agu/fm19/meetingapp.cgi/Paper/614572, accessed January 2020.

Lodge TE. 2010. The Everglades handbook: understanding the ecosystem. 3rd ed. Boca Raton, FL: CRC Press.

Marshall FE III, Wingard L, Pitts P. 2009. A simulation of historic hydrology and salinity in Everglades National Park: coupling paleoecologic assemblage data with regression models. Estuaries Coast. 32:37–53.

McIvor CC, Ley JA, Bjork RD. 1994. Changes in freshwater inflow from the Everglades to Florida Bay including effects on the biota and biotic processes: a review. In: Davis SM, Ogden JC, editors. Everglades: the ecosystem and its restoration. Boca Raton, FL: CRC Press. p. 117–146.

Meeder JF, Parkinson RW, Ruiz PL, Ross MS. 2017. Saltwater encroachment and prediction of future ecosystem response to the Anthropocene marine transgression, Southeast Saline Everglades, Florida. Hydrobiologia. 803:29–48.

Moser J, Shamblin RB, Fotinos TA, Atkinson AJ, et al. 2019. South Florida/Caribbean network mangrove–marsh ecotone monitoring: protocol narrative. Natural Resource Report NPS/SFCN/NRR—2019/1923. Fort Collins, CO: U.S. National Park Service, Natural Resource Stewardship and Science. Available from https://irma.nps.gov/DataStore/DownloadFile/626118.

Neigh CS, Masek JG, Nickeson JE. 2013. High-resolution satellite data open for government research. Eos. 94(13):121–123.

Olmsted IC, Armentano TV. 1997. Vegetation of Shark Slough, Everglades National Park. Homestead, FL: Everglades National Park. South Florida Natural Resources Center Report 97-001. Available from https://www.nps.gov/ever/learn/nature/upload/SecureTRSFNRC97-001.pdf.

Osland MJ, Feher LC, Anderson GH, Vervaeke WC, et al. 2020. A tropical cyclone–induced ecological regime shift: mangrove forest conversion to mudflat in Everglades National Park (Florida, USA). Wetlands 40:1445–1458.

Pasch RJ, Blake ES, Cobb III HD, Roberts DP. 2006. Tropical cyclone report, Hurricane Wilma, 15–25 October 2005. Miami, FL: National Hurricane Center. Available from https://www.nhc.noaa.gov/data/tcr/AL252005_Wilma.pdf.

Perry W. 2004. Elements of South Florida's Comprehensive Everglades Restoration Plan. Ecotoxicology. 13:185–193.

Radabaugh KR, Moyer RP, Chappel AR, Dontis EE, et al. 2020. Mangrove damage, delayed mortality, and early recovery following Hurricane Irma at two landfall sites in southwest Florida, USA. Estuar Coast. Special issue: Impact of 2017 Hurricanes 43: 1104–1118.

Ross MJ, Meeder JF, Sah JP, Ruiz PL, Telesnicki GJ. 2000. The Southeast Saline Everglades revisited: 50 years of coastal vegetation change. J Veg Sci. 11:101–112.

Ross MS, Gaiser EE, Meeder JF, Lewin MT. 2002. Multi-taxon analysis of the "white zone," a common ecotonal feature of South Florida coastal wetlands. In: Porter JW, Porter KG, editors. The Everglades, Florida Bay, and coral reefs of the Florida Keys: an ecosystem sourcebook. Boca Raton, FL: CRC Press. p. 205–238.

Ruiz PL, Giannini HC, Prats MC, Perry CP, et al. 2017. The Everglades National Park and Big Cypress National Preserve vegetation mapping project: interim report, Southeast Saline Everglades (Region 2), Everglades National Park. Fort Collins, CO: U.S. National Park Service. Natural Resource Report NPS/SFCN/NRR—2017/1494. Report available from https://irma.nps.gov/Datastore/DownloadFile/583479, map available from https://irma.nps.gov/Datastore/Reference/Profile/2244641.

Ruiz PL, Lee A, Thompson C, Castillo I, et al. 2019. The Everglades National Park and Big Cypress National Preserve vegetation mapping project: interim report, Eastern Big Cypress (Regions 5 & 6), Big Cypress National Preserve. Fort Collins, CO: U.S. National Park Service. Natural Resource Report NPS/SFCN/NRR—2019/2035. Report available from https://irma.nps.gov/Datastore/Reference/Profile/2267127, map available from https://irma.nps.gov/Datastore/Reference/Profile/2267445.

Ruiz PL, Perry CP, Garcia AA, Guichardot M, et al. 2020. The Everglades National Park and Big Cypress National Preserve vegetation mapping project: interim report, Northwest Coastal Everglades (Region 4), Everglades National Park. Fort Collins, CO: U.S. National Park Service. Natural Resource Report NPS/SFCN/NRR—2020/2133. Report available from https://irma.nps.gov/Datastore/Reference/Profile/2274300, map available from https://irma.nps.gov/Datastore/Reference/Profile/2274129.

Ruiz PL, Prats MC, Perry CP, Garcia AA, et al. 2018. The Everglades National Park and Big Cypress National Preserve vegetation mapping project: interim report, Southwest Coastal Everglades (Region 3), Everglades National Park. Fort Collins, CO: U.S. National Park Service. Natural Resource Report NPS/SFCN/NRR—1776. Report available from https://irma.nps.gov/Datastore/Reference/Profile/2256787, map available from https://irma.nps.gov/Datastore/Reference/Profile/2257752.

Sandoval E, Price RM, Whitman D, Melesse AM. 2016. Long-term (11 years) study of water balance, flushing times and water chemistry of a coastal wetland undergoing restoration, Everglades, Florida, USA. Catena. 144:74–83.

Schall TN, Ruiz PL, Rutchey K, Irving C, et al. 2020. The Everglades National Park and Big Cypress National Preserve vegetation mapping project: interim report, Shark River Slough/Long Pine Key (Region 1), Everglades National Park. Jacksonville, FL: US Army Corps of Engineers, Jacksonville District. Available from https://usace.contentdm.oclc.org/utils/getfile/collection/p16021coll7/id/16045.

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

SFWMD (South Florida Water Management District). 2018. Land cover land use 2014–2016. https://sfwmd.maps.arcgis.com/home/item.html?id=266a64a897514090842e283311c12d30, accessed November 2019.

Simard M, Zhang K, Rivera-Monroy VH, Ross MS, et al. 2006. Mapping height and biomass of mangrove forests in Everglades National Park with SRTM elevation data. Photogramm Eng Remote Sensing. 72:299–311.

Smith TJ III, Anderson GH, Balentine K, Tiling G, et al. 2009 Cumulative impacts of hurricanes on Florida mangrove ecosystems: sediment deposition, storm surges and vegetation. Wetlands. 29(1):24–34.

Smith TJ III, Foster AM, Tiling-Range G, Jones JW. 2013. Dynamics of mangrove-marsh ecotones in subtropical coastal wetlands: fire, sea-level rise, and water levels. Fire Ecology. 9:66–77.

Smith TJ III, Hudson HJ, Robblee MB, Powell GN, Isdale PJ. 1989. Freshwater flow from the Everglades to Florida Bay: a historical reconstruction based on fluorescent banding in the coral *Solenastrea bournoni*. Bull Mar Sci. 44(1):274–282.

Smith TJ III, Robblee MB, Wanless HR, Doyle TW. 1994. Mangroves, hurricanes, and lightning strikes: assessment of Hurricane Andrew suggests an interaction across two differing scales of disturbance. BioScience. 44:256–262.

Smoak JM, Breithaupt JL, Smith TJ III, Sanders CJ. 2013. Sediment accretion and organic carbon burial relative to sea-level rise and storm events in two mangrove forests in Everglades National Park. Catena. 104:58–66.

Soderqvist LE, Byrne MJ. 2007. Monitoring the storm tide of Hurricane Wilma in southwestern Florida, October 2005. Reston, VA: U.S. Geological Survey. Data Series 294. Available from https://pubs.usgs.gov/ds/2007/294/pdf/ds294_Soderqvist.pdf.

Stansfield AM, Reed KA, Zarzycki CM. 2020. Changes in precipitation from north Atlantic tropical cyclones under RCP scenarios in the variable-resolution Community Atmosphere Model.

Geophys Res Lett. 47: e2019GL086930. https://doi.org/10.1029/2019GL086930

Taillie P, Roman-Cuesta R, Lagomasino D, Cifuentes-Jara M, et al. 2020. Widespread mangrove damage resulting from the 2017 Atlantic mega hurricane season. Environ Res Lett. 15(6):064010.

USFWS (U.S. Fish and Wildlife Service). 1999. The South Florida ecosystem. In: Multi-species recovery plan. Atlanta, GA: USFWS Southeast Region. p. 2-1 to 2-8 https://www.fws.gov/verobeach/listedspeciesMSRP.html, accessed April 2020.

USNPS (U.S. National Park Service). 1979. Everglades National Park master plan. Available from https://www.nrc.gov/docs/ML1219/ML12193A250.pdf.

USNPS (U.S. National Park Service). 2006. South Florida and Caribbean parks exotic plant management plan and environmental impact statement, Volume 1. https://parkplanning.nps.gov/document.rkID=374&projectID=10033&documentID=16855, accessed June 2020.

Wanless HR, Parkinson RW, Tedesco IP. 1994. Sea-level control on stability of Everglades wetlands. In: Davis SM, Ogden JC, editors. Everglades: the ecosystem and its restoration. Boca Raton, FL: CRC Press.

Wanless HR, Vlaswinkel BM. 2005. Coastal landscape and channel evolution affecting critical habitats at Cape Sable, Everglades National Park, Florida. Washington, DC: U.S. National Park Service. Paleo-Everglades Drainage. Final Report. Available from https://www.nps.gov/ever/learn/nature/upload/SecureCapeSableFinalReport050615.pdf.

Whelan KRT, Prats M, Atkinson AJ. 2020. Western Big Cypress National Preserve vegetation map. Fort Collins, CO: U.S. National Park Service. Natural Resource Report NPS/SFCN/NRR—2020/2170. Available from https://irma.nps.gov/DataStore/Reference/Profile/2278515.

Whelan KR, Smith TJ III, Anderson GH, Ouellette ML. 2009. Hurricane Wilma's impact on overall soil elevation and zones within the soil profile in a mangrove forest. Wetlands 29(1):16–23.

White JC, Wulder MA, Varhola A, Vastaranta M, et al. 2013. A best practices guide for generating forest inventory attributes from airborne laser scanning data using an area-based approach. For Chron. 89:722–723.

Wingard GL, Bergstresser SE, Stackhouse BL, Jones MC, et al. 2020. Impacts of Hurricane Irma on Florida Bay Islands, Everglades National Park, USA. Estuaries Coast. Special Issue: Impact of 2017 Hurricanes 43:1070–1089.

Wingard GL, Lorenz J. 2013. Habitat: coastal wetlands. In: Nuttle WK, Fletcher PJ, editors. Integrated conceptual ecosystem model development for the southwest Florida shelf coastal marine ecosystem. Miami, FL: National Oceanic and Atmospheric Administration. p. 87–108. NOAA Technical Memorandum, OAR-AOML-102 and NOS-NCCOS-162. Available from https://www.aoml.noaa.gov/general/lib/TM/TM_OAR_AOML_102.pdf.

Zhai L, Zhang B, Roy SS, Fuller DO, Sternberg LD. 2019. Remote sensing of unhelpful resilience to sea level rise caused by mangrove expansion: a case study of islands in Florida Bay, USA. Ecol Indic. 97:51–58.

Zhang C, Durgan SD, Lagomasino D. 2019. Modeling risk of mangroves to tropical cyclones: a case study of Hurricane Irma. Estuar Coast Shelf Sci. 224:108–116.

Zhang K. 2011. Analysis of non-linear inundation from sea-level rise using LIDAR data: a case study for South Florida. Clim Change. 106:537–565.

General references and additional regional information

Comprehensive Everglades Restoration Program https://evergladesrestoration.gov/

Everglades National Park https://www.nps.gov/ever/index.htm

Florida Coastal Everglades Long Term Ecological Research Network https://fcelter.fiu.edu/

Gulf Coastal Plains and Ozarks Landscape Conservation Cooperative, Compilation of Gulf of Mexico Surface Elevation Tables (SETS) https://gcpolcc.databasin.org/datasets/6a71b8fb60224720b903c770b8a93929

National Parks Conservation Association, State of the Parks https://www.npca.org/resources/1138-center-for-state-of-the-parks-florida-bay#sm.0000o5ohzabcwdf6zwl1hwpkh5khb

South Florida/Caribbean Network https://www.nps.gov/im/sfcn/index.htm

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