

Chapter 7

Collier County

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Description of the region

The coast of Collier County includes the urbanized areas of Naples and Marco Island as well as a network of protected lands with large, uninterrupted areas of coastal habitat (Figure 7.1). These coastal public lands include the Rookery Bay National Estuarine Research Reserve (NERR), which encompasses the Rookery Bay Aquatic Preserve and the Cape Romano–Ten Thousand Islands Aquatic Preserve, Ten Thousand Islands National Wildlife Refuge (NWR), Collier–Seminole State Park, and the western extent of Everglades National Park. Coastal estuarine waters are generally shallow; coastal water in Ten Thousand Islands NWR has a mean depth of 3 m (10 ft) (USFWS 2000). Salinity varies widely with freshwater inflow, generally staying above 34 in the dry season and fluctuating from 20 to 32 in the wet season (Soderqvist and Patino 2010). The substrate is Miami limestone from the Miocene, which is overlaid by a poorly drained assortment of late Pleistocene sands, organic material, oyster shell, and mangrove peat (USFWS 2000). The formation of the numerous islands that give the Ten Thousand Islands its name is a result of oyster and vermetid gastropod reefs formed during the early to middle Holocene (Volety et al. 2009). Mangrove propagules took root on these reefs and matured to the mangrove islands found today (Figure 7.1).

The extensive network of small islands along the coastline results in a high edge-to-area ratio in these island mangrove forests. Red mangrove (*Rhizophora mangle*) is commonly found along the fringe of coastal islands

and tidal creeks. Black mangrove (*Avicennia germinans*) is the most abundant species in interior basin forests. Both black mangrove and white mangrove (*Laguncularia racemosa*) are found at higher elevations or in disturbed areas, usually on the interior and landward side of the forest. Buttonwood (*Conocarpus erectus*) is common in areas of slightly higher elevation, such as on ridges along levees or on beach strands.

Mangroves dominate the coast, while salt marshes dominated by cordgrasses (*Spartina* spp.), black needlerush (*Juncus roemerianus*), and salt grass (*Distichlis spicata*) occur further inland (Figure 7.1). Most of the salt marshes lack a direct tidal connection but flood at high tides and during storms. Coastal ponds containing saline, brackish, or fresh water are also found in close association with the salt marshes (Andres et al. 2019). Upland habitat is not common along the coast due to the low elevation, although shell mounds from Native American populations and some small sandy dunes provide some local variability (USFWS 2000, Barry et al. 2013, Barry and van der Heiden 2015).

Powerful hurricanes in 1918 and 1935 and Hurricane Donna in 1960 caused massive deforestation in the region, so most of the mangroves are second-growth forests (USFWS 2000, FDEP 2012). More recently, hurricanes Andrew in 1992, Wilma in 2005, and Irma in 2017 also caused extensive damage to the mangroves (Smith et al. 1994, FDEP 2012, Radabaugh et al. 2020, McCarthy et al. 2020). Andrew caused slightly more tree loss in island mangroves,

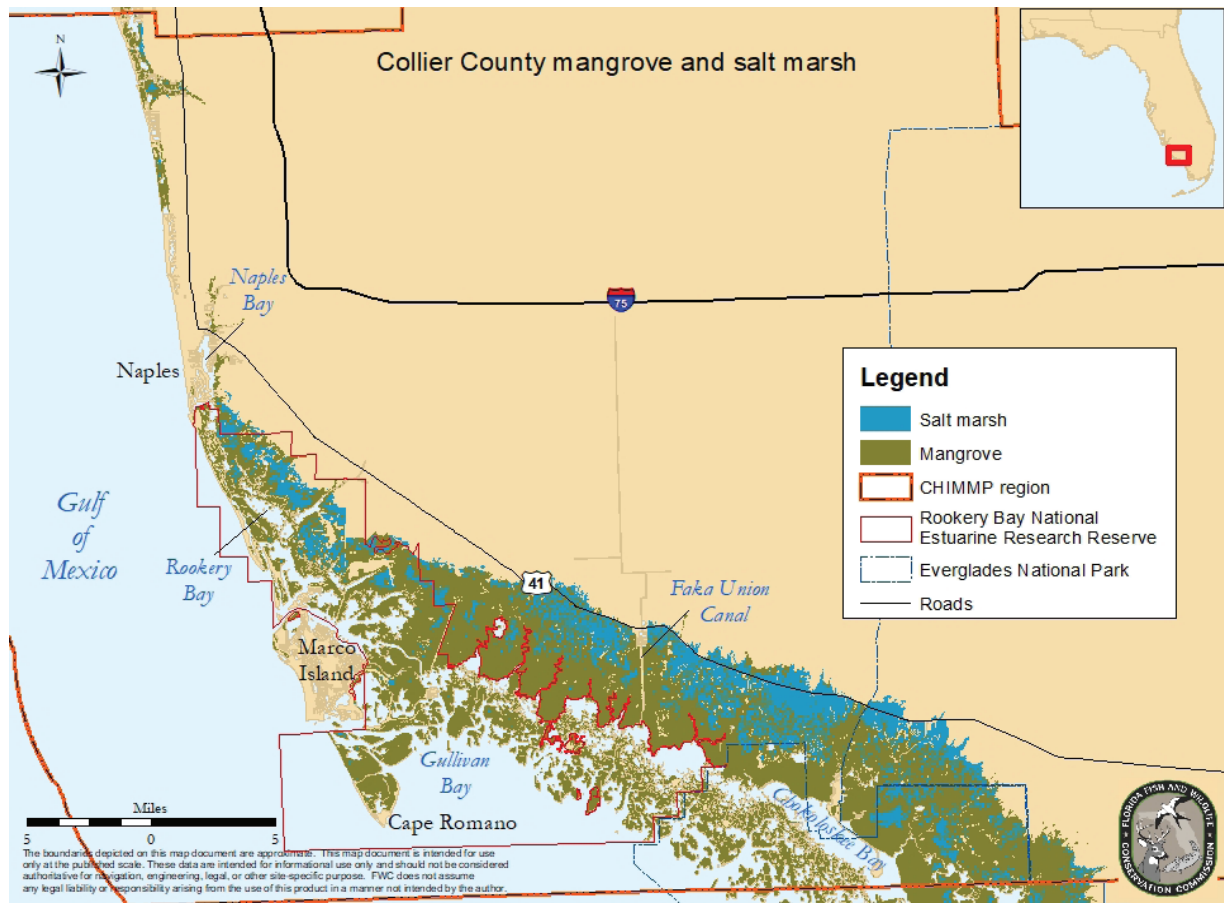


Figure 7.1. Mangrove and salt marsh extent in Collier County, Florida, according to SFWMD 2014–2016 land-use/land-cover data following FLUCCS classifications (FDOT 1999, SFWMD 2018).

while Wilma caused significantly more damage in basin forests and set back recovery of the forests following Andrew (Smith et al. 2009). Most recently, Irma made landfall 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) (Canglialosi et al. 2018). Inundation due to storm surge was 1.8–3.0 m (6–10 ft) above ground level within Everglades National Park and the Ten Thousand Islands NWR (Canglialosi et al. 2018). Irma decimated mangrove islands along the coast, including both fringe and basin forests. Recovery has been slow (Figure 7.2), and mangrove mortality was particularly high in black mangrove basin forests (Chavez et al. 2019, Lagomasino et al. 2019) and areas with thick storm surge deposits of marine-origin carbonate mud (Radabaugh et al. 2020).

Human development and hydrologic alterations

Rapid coastal development and a lack of environmental regulation before 1970 resulted in extensive loss and alteration of wetlands in Collier County (USFWS 2000).

This loss was followed by a period of rapid population growth; from 1980 to 1998, the population of the county increased by 144% (FDEP 2012). With a population of 385,000 in 2019, the population of Collier County is less than that of other urban centers in south Florida. However, the population grew an estimated 19.7% from 2010 to 2019, outpacing the state growth average of 14.2% during this time (U.S. Census 2020). Tourism, commercial fishing, and sportfishing are central components of the economy.

The once extensive mangrove shoreline along Naples and Marco Island has been irreversibly transformed by development and hydrologic alterations (Turner and Lewis 1997). Mangrove fringe adjacent to urban areas was removed to pave the way for residential developments and commercial ventures. Naples Bay lost more than 70% of its fringing mangrove shoreline in the 1950s and 1960s, when extensive dredge-and-fill operations and shoreline modifications made way for residential communities (FDER 1981, Schmid et al. 2006). Mangroves were extensively removed on Marco Island in the 1960s and 1970s to make way for the present framework of homes fronting



Figure 7.2. Collier County examples of a recovering mangrove forest 9 months following Hurricane Irma (left) and mangrove mortality 16 months after Irma (right). Photo credits: Kara Radabaugh and Matthew McCarthy, respectively.

dredged canals. Although human development has been extensive in many parts of the county, large tracts of protected land and mangrove expansion have enabled mangroves to retain 70% of their original extent in the Rookery Bay watershed and to exceed their historical extent in the Ten Thousand Islands watershed (CSF 2011).

The extent of remaining mangrove forests has increased in Collier County as the trees encroach into salt marshes. This transition has resulted from changes in hydrology, including the diverting of water flow by drainage canals, the impeding of surface freshwater flow by U.S. 41, and sea-level rise (Krauss et al. 2011, Barry and van der Heiden 2015, Howard et al. 2020). Mangrove extent in Ten Thousand Islands NWR increased 35%, or 1,878 ha (4,640 ac), from 1927 to 2005 (Krauss et al. 2011). Constructed waterways, such as the Faka Union Canal (Figure 7.1), facilitate mangrove expansion by increasing the upstream reach of tidal influence, which enhances the inland dispersal of mangrove propagules (Krauss et al. 2011).

Human development in the northern part of the watershed has led to downstream water quality problems along the coast. Eighty-five percent of the Rookery Bay watershed and 100% of the Ten Thousand Islands watershed is impaired for at least one parameter such as low

dissolved oxygen, high nutrients, and increased levels of mercury or other pollutants (CSF 2011). A series of canals were dug by the Gulf American Corporation during 1963–1971 to drain extensive areas for the planned South Golden Gate Estates development. These canals connect to the Faka Union Canal and discharge at Port of the Islands, resulting in increased seasonal freshwater flow and turbidity, along with decreased fish diversity and seagrass extent in Ten Thousand Islands NWR (USFWS 2000, Shrestha et al. 2011). Much of the planned South Golden Gate Estates was not developed, and the State of Florida purchased most of the private lots from 1998 to 2001 to implement the hydrologic restoration plan for the region, now known as Picayune Strand State Forest (SFWMD and USDA 2003). The restoration plan aims to restore hydrology by partly filling canals, pumping surface water through spreader channels, and de-grading roads to restore more natural sheet flow (USFWS 2000, SFWMD and USDA 2003). The first of three pump stations for the restoration effort was opened in 2014 (Staats 2014). Additional efforts to improve sheet flow in the Ten Thousand Island region include the installation of 62 culverts along 77 km (48 miles) of Tamiami Trail (U.S. 41) in Collier County from 2004 to 2006 (Abtew and Ciuca 2011).

Threats to coastal wetlands

Coastal wetlands are threatened by a variety of anthropogenic and natural phenomena. Finn et al. (1997) classified 15 causes of mangrove mortality in the area including lightning strikes, hurricanes, frost, and human impacts. The most prominent threats in southwest Florida include the following:

- **Peat collapse:** In southwest Florida, mortality of predominantly black mangrove basin forests can occur as a result of an extended period of surface-water retention due to impoundment, increased surface-water runoff, storm surge, or other cause of increased inundation leading to prolonged submersion and inhibited gas exchange by the mangroves' pneumatophores. This stress can eventually kill the mangrove, and the subsequent decay of biomass belowground can cause peat collapse, decreasing elevation and resulting in further inundation (Worley 2005, Lewis et al. 2016, Krauss et al. 2018). Lewis et al. (2016) referred to this situation of blocked tidal flow leading to stagnant water and subsequent mangrove mortality as a mangrove heart attack.

An analogous phenomenon of altered hydrology, vegetation death, and peat collapse also occurs in salt marshes, including those in Collier County (Andres et al. 2019). Interior salt marshes develop subtidal ponds, sometimes called pocks, in response to degradation of surficial peat and elevation loss (Andres et al. 2019, Howard et al. 2020). The sides of pocks can erode over time, leading to ponds that expand in size or merge with each other (Andres et al. 2019). Because of the escalating nature of peat collapse, both pocks and mangrove heart attacks frequently grow in size and severity (Lewis et al. 2016, Krauss et al. 2018, Andres et al. 2019).

- **Coastal development and altered hydrology:** Urban construction has been linked to many instances of mangrove mortality in Collier County. For instance, in the 1990s, urban and road construction along Clam Bay led to altered hydrology and widespread death of black mangroves (Worley and Schmid 2010). While much of Collier County is now conservation land, population growth and development continue, particularly along State Road 951 and south of U.S. 41. This development continues to impact coastal wetlands via habitat destruction, impaired water quality, and altered hydrology, such as that resulting when roads block tidal exchange (Zysko 2011). Development along some regions of coastal Collier County also block mangroves and salt marsh from migrating inland in response to sea-level rise, pinching out coastal wetlands.

- **Hurricanes:** Hurricanes and tropical storms alter the structure of mangrove forests by causing widespread canopy damage and mortality which may vary by species, tree size, or location in the forest (Smith et al. 2009, Radabaugh et al. 2020). Peat collapse is also suspected of causing mortality after hurricanes and is thought to have been responsible for mortality of black mangrove basin forests following the 1935 Labor Day hurricane and Hurricane Donna in 1960 (Wanless et al. 1995). Widespread mortality of black mangrove basin forests also occurred following Hurricane Irma (Chavez et al. 2019, Lagomasino et al. 2019, McCarthy et al. 2020, Radabaugh et al. 2020, Tallie et al. 2020).
- **Climate change and sea-level rise:** Mangroves have already overtaken significant expanses of salt marsh and brackish marsh as they have expanded inland, primarily as a response to rising sea level (Krauss et al. 2011, Barry et al. 2013, Barry and van der Heiden 2015). Sea-level rise also enables mangrove expansion into salt barrens. The tidal flushing provided by a small increase in sea level can decrease the hypersaline conditions of the salt barren, creating favorable conditions for colonization by mangroves.

The ability of salt marshes and mangroves to maintain their present extent will depend upon their ability to accrete substrate at a rate equal to or exceeding the rate of sea-level rise. Recent research has found that the rate of carbon burial has increased over the past 100 years in southwest Florida mangroves (Breithaupt et al. 2020), and forest elevation is further increased by hurricane deposits (Feher et al. 2020). But sediment elevation table (SET) monitoring has shown that the elevation of the substrate in local salt marshes is decreasing (Howard et al. 2020).

- **Disease and other biotic factors:** Disease is usually not the root cause of mortality in coastal wetland forests; rather, diseases tend to occur in areas being stressed by other influences (Jimenez et al. 1985). A fungus found in mangrove forests in Collier County, *Cytospora rhizophorae*, is a classic example. This fungus tends to attack stressed red mangrove trees and can have a mortality rate as high as 32% (Wier et al. 2000). Similarly, infestations by wood-boring insects and isopods are not uncommon (Worley 2019). These infestations are generally not fatal, but they do alter growth patterns of mangrove trees (Simberloff et al. 1978). Similarly, after the cold snap in the winter of 2008, some parts of mangrove forests became infested with wood-boring beetles (Roy R. [Robin] Lewis III, pers. obs.). Under healthy conditions, these boring beetles tend to attack living

twigs or branches, but the tree usually recovers. When trees are under stress, severe infestations are more likely to develop, possibly to the extent that the trees become girdled and die (Feller and Mathis 1997, Feller and McKee 1999). Given that stresses to coastal wetlands are likely to increase due to anthropogenic and natural causes, the influence of diseases and infestations on mortality rates could also increase.

- **Invasive vegetation:** Invasive vegetation, mainly Brazilian pepper (*Schinus terebinthifolia*) but also Australian pines (*Casuarina* spp.), melaleuca (*Melaleuca quinquenervia*), and latherleaf (*Colubrina asiatica*) tend to dominate along the fringe of marsh and mangrove forests in the region (USFWS 2000, Barry et al. 2013, Barry and van der Heiden 2015). Removal efforts are ongoing as funding is available.

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 within the district. Figure 7.1 shows the 2014–2016 LULC map (SFWMD 2018), which was the most recent SFWMD LULC map of Collier County available at publication. Land-cover classifications are based on SFWMD modifications to the Florida Land Use, Cover and Forms Classification System (FLUCCS; FDOT 1999). Minimum mapping units were 2 ha (5 ac) for uplands and 0.2 ha (0.5 ac) for wetlands. The 2014–2016 maps were made by interpreting aerial photography and updating 2008–2009 LULC vector data.

Fine-scale vegetation mapping

The southwest coast of Collier County was mapped according to the Comprehensive Everglades Restoration Plan (CERP) by the Institute for Regional Conservation (IRC) with a focus on vegetation composition (Figures 7.3 and 7.4). Completed vegetation maps include those for Rookery Bay NERR (Barry et al. 2013, Barry and van der Heiden 2015), Ten Thousand Island NWR (Barry 2009), and Picayune Strand State Forest. Each land-management agency has been responsible for finding funding under which to contract with Mike Barry (formerly with the IRC, now independently contracting) to conduct the ongoing mapping. Having the same person conduct the mapping for all the agencies has provided a contiguous map with consistent methodology. The vegetation maps were created based on extensive field work, multiple years

of aerial photography interpretation, and LiDAR (light detection and ranging) surveys. The field data collection included photo points and GPS track logs with observed vegetation, including the presence of nonnative and rare native vegetation. A historical vegetation map was created by integrating field observations, interviews with longtime residents, and 1940 aerial photography. Habitat mapping in Rookery Bay NERR has documented widespread mangrove mortality within the reserve (Barry et al. 2013). Overall, vegetation analysis from 1940 through 2010 revealed that salt marshes have changed the most, shifting overwhelmingly toward mangrove-dominated communities (Barry and van der Heiden 2015). These dramatic changes are attributed to sea-level rise and hydrologic alterations.



Figure 7.3. Photo composites in November 2010 (top) and January 2020 (bottom) in Rookery Bay NERR showing a decline in pine trees (*Pinus* sp.) and saw palmettos (*Serenoa repens*) and an increase in leatherfern (*Acrostichum* sp.) and buttonwood (*Conocarpus erectus*). Vegetation changes were related to sea-level rise, Hurricane Irma, and a recent prescribed burn. Photo credit: Mike Barry.

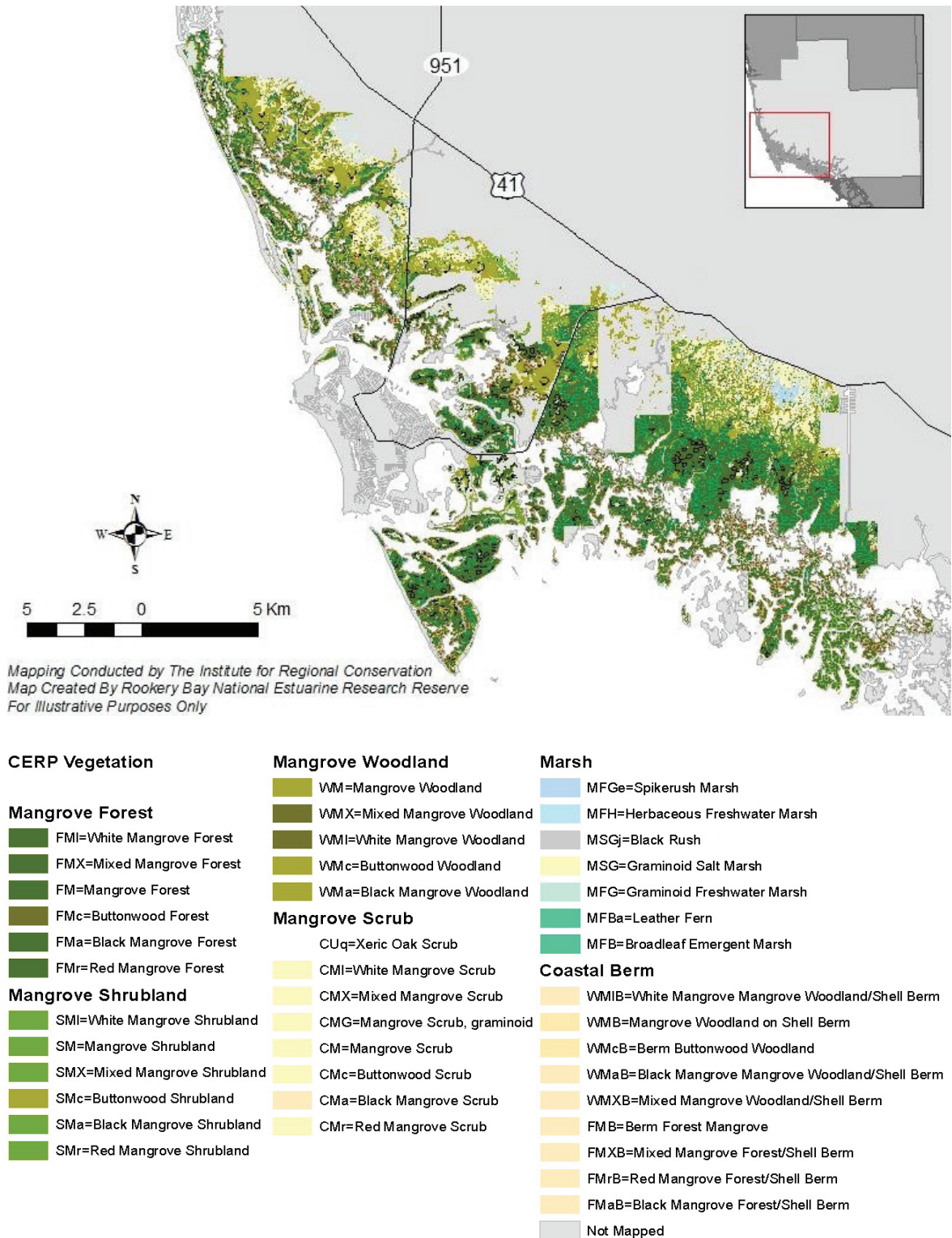


Figure 7.4. Salt marsh and mangrove vegetation mapped in the Rookery Bay NERR (Barry et al. 2013) and Ten Thousand Islands NWR (Barry 2009) according to CERP classifications (Rutchev et al. 2006).

Vegetation classifications in the fine-scale vegetation maps follow the categories used by CERP (Rutchev et al. 2006), the Florida Natural Areas Inventory (FNAI 2010), and FLUCCS (FDOT 1999). Figure 7.4 illustrates the level of detail inherent in the classification, which is necessary for detecting subtle changes in vegetation that might be associated with anthropogenic influences and effects of sea-level rise, such as movement of salt-tolerant vegetation into upland habitat (e.g., Figure 7.3). These fine-scale maps are especially important as they have established baseline data on the extent and cover of specific vegetative communities and can be used to document future changes.

Rookery Bay NERR recently started a National Oceanic and Atmospheric Administration Sentinel Site (NOAA 2016) along Henderson Creek to monitor changes in elevation, vegetation structure, and groundwater levels. The Sentinel Site monitoring program there will include updated fine-scale vegetation mapping in the transitional zones of this area approximately every five years.

Marco Island mapping

Patterson (1986) mapped mangrove habitats in the Marco Island area using aerial photography from 1984, 1973, 1962, and 1952 and examined the change in extent

of mangrove communities among aerial photographs. He performed an accuracy assessment on the maps with ground truthing and helicopter surveys. Patterson (1986) calculated that the total mangrove acreage in the Marco Island area declined from 4,566 ha (11,285 ac) to 3,470 ha (8,574 ac) from 1952 to 1984. The decline was due primarily to the residential development of Marco Island, but hurricanes during the 1960s also contributed.

Florida Gulf Coast University mangrove stress mapping

Neafsey (2014) mapped areas of mangrove stress through a combination of imagery interpretation (Esri basemap) and field surveys using the SFWMD's definition of mangrove forests. Results are shown in Figure 7.5. An index was created for mapping the status of mangrove forests on a scale of 1 to 5:

1. functional mangrove, no exotics, and no impoundments (26,859 ha/66,370 ac)
2. mosquito ditching (151 ha/373 ac)
3. impoundments (285 ha/704 ac)
4. impoundments and mosquito ditching (34 ha/84 ac)
5. zones of mangrove mortality (including mangrove heart attacks) (94 ha/232 ac)



Figure 7.5. Mangrove stress (before Hurricane Irma) in Rookery Bay and Ten Thousand Islands on a scale of 1 to 5 (modified from Neafsey 2014; see text above for description).

Before Hurricane Irma, results indicated that 564 ha (1,394 ac) of the total 27,423 ha (67,763 ac) examined were stressed or dead, amounting to 2% of the surveyed mangroves. Focusing on an area of high mangrove mortality, the Conservancy of Southwest Florida (CSF) and Coastal Resources Group Inc. found that more than half of the 404 ha (1,000 ac) of mangroves surveyed near Goodland were stressed or dead (Krauss et al. 2018; see Fruit Farm Creek restoration explanation below).

Ongoing mapping work at Florida Gulf Coast University is focused on the use of the U.S. Department of Agriculture Farm Service Agency's National Agricultural Imagery Program (NAIP) 2018 mosaic to assess mangrove canopy loss from Hurricane Irma. NAIP images have a derived normalized difference vegetation index (NDVI) product (Esri and USDA 2018), which can serve as a consistent, high-resolution indicator of post-Irma canopy loss in the pre-hurricane-stress-level zones mentioned above.

Mapping and monitoring Hurricane Irma damage and recovery

Since Hurricane Irma, multiple mapping and monitoring efforts have examined the extensive damage it caused and the ongoing recovery of the mangrove forests. These studies, conducted in situ or via remote sensing, include the following:

- **Florida Fish and Wildlife Conservation Commission (FWC) monitoring:** Damage following Hurricane Irma was monitored in several locations in the Ten Thousand Islands and Lower Florida Keys by the FWC Fish and Wildlife Research Institute from 2017 through 2019. Vegetation monitoring in 10-m × 10-m plots included quantification of tree mortality, soil shear strength, root growth rates, canopy recovery, and understory development (Radabaugh et al. 2020). Taller mangroves had greater tree mortality, more downed wood, and more severe canopy damage than did shorter forests. Many mangroves that initially survived the hurricane died several months later; this delayed mortality was linked to thickness of carbonate mud deposited on the forest floor by storm-surge flooding. Additional monitoring activities were focused on the thinning, transformation, and microbiota of this storm-surge deposit over time.
- **Remote sensing mapping and monitoring:** Remote-sensing monitoring of coastal areas in southwest Florida was conducted by NASA Goddard's LiDAR, 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. About 25% of the approximate 130,000 ha (320,000 ac) covered by the G-LiHT campaign included coastal regions of Collier County, particularly around the Ten Thousand Islands region. This instrument has been used primarily to augment forest inventory surveys (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 G-LiHT LiDAR data and high-resolution aerial photos were combined with satellite observations to estimate that 332 km² (128 mi²) of mangrove forests across south Florida were severely damaged by Hurricane Irma (Zhang et al. 2019). Recent reports use multiple satellite observations between December 2017 and December 2018 to estimate the extent of mortality and the change in mangrove forest composition caused by delayed mortality from extended ponding (Lagomasino et al. 2019).

- **University of South Florida mapping of mangrove loss:** Additional remote-sensing assessment of mangrove damage was conducted using a time series of high-resolution (2 m/6.6 ft) satellite imagery. WorldView-2 images were acquired by researchers at the University of South Florida (USF) from 2010 through 2018 and mapped using automated methods on the USF supercomputer (McCarthy et al. 2018) to identify healthy and damaged mangroves within the Rookery Bay NERR at seasonal to interannual time steps. Ground-truthing in fall 2018 verified that the maps were 82% accurate. Maps produced from spring 2017 (i.e., pre-Irma) to winter 2017–2018 found that Hurricane Irma had damaged approximately 6 km² (2.3 mi²) of mangroves (i.e., 23% of the studied area; Figure 7.6). Following one growing season, fall 2018 maps indicated that 3 km² (1.2 mi²) had recovered, while some areas of initially degraded mangrove died back, exposing soil (Figure 7.7). Imagery from spring 2016 allowed for a baseline assessment of mangrove health that indicated that Rookery Bay NERR lost a total of 6.85 km² (2.6 mi²) from 2016 through 2018 as a result of both Hurricane Irma and chronic stressors such as hydrologic impoundments and sea-level rise (McCarthy et al. 2020).

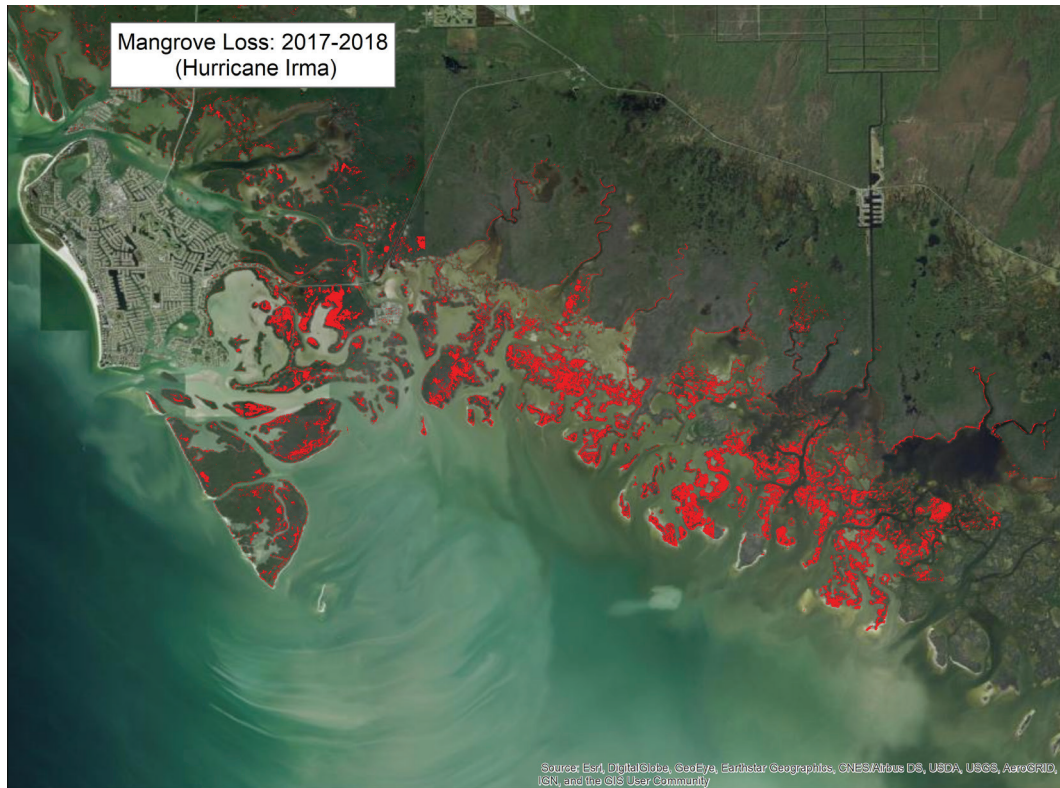


Figure 7.6. Damage to mangrove forests caused by Hurricane Irma within Rookery Bay NERR and Ten Thousand Islands NWR as observed from WorldView 2 satellite imagery. Red areas were classified as healthy mangrove forests in early 2017, then as degraded mangrove forests or bare soil in March 2018.

Storm surge reduction by mangroves

Models and direct measurements from southwest Florida clearly demonstrate that mangroves can reduce storm-surge height during hurricanes (Krauss et al. 2009, Liu et al. 2013, Montgomery et al. 2019, Narayan et al. 2019). Wider swaths of mangrove forests provide the greatest protection (Narayan et al. 2019), and unchanneled forests are more effective at reducing storm surge than are mangroves along river corridors (Krauss et al. 2009). Mangrove reduction of storm surge is greater for fast-moving, weak hurricanes than for slower, strong hurricanes (Liu et al. 2013). During Hurricane Irma, flood risk was reduced by 25% for Collier County properties located behind mangrove forests (Narayan et al. 2019). Across south Florida, mangroves prevented an estimated \$1.5 billion in property damages during Hurricane Irma (Narayan et al. 2019).

Monitoring restoration projects

Numerous mangrove and hydrologic restoration projects were carried out in Collier County during the past 20 years; selected examples are described below. Monitor-

ing efforts are still under way in a few of these projects and have provided valuable information to guide management and restoration decisions for stressed and dead mangroves.

- Fruit Farm Creek:** This phased mangrove restoration effort was initiated in 2000. Preliminary studies by CSF investigated the factors, such as restricted tidal flow by San Marco Road, that contributed to the nearly 240 ha (600 ac) of dead and stressed mangroves near Goodland. The substrate in the areas of mangrove mortality showed signs of peat collapse, as evidenced by compaction in and below the root zone (Krauss et al. 2018). A multiagency organizational group led by the Coastal Resources Group Inc. was formed in 2005 and created restoration plans for a two-phase program covering 103 ha (225 ac). Tidal exchange to a 1.6-ha (4 ac) test site in the area with extensive mortality was restored in 2012 with funding from the U.S. Fish and Wildlife Service (USFWS) Coastal Program and was monitored by CSF and the Coastal Resources Group Inc. This hydrologic restoration program (Turner and Lewis 1997) followed the basic principles of ecological mangrove restoration outlined by Lewis (2005) and Lewis and Brown (2014),

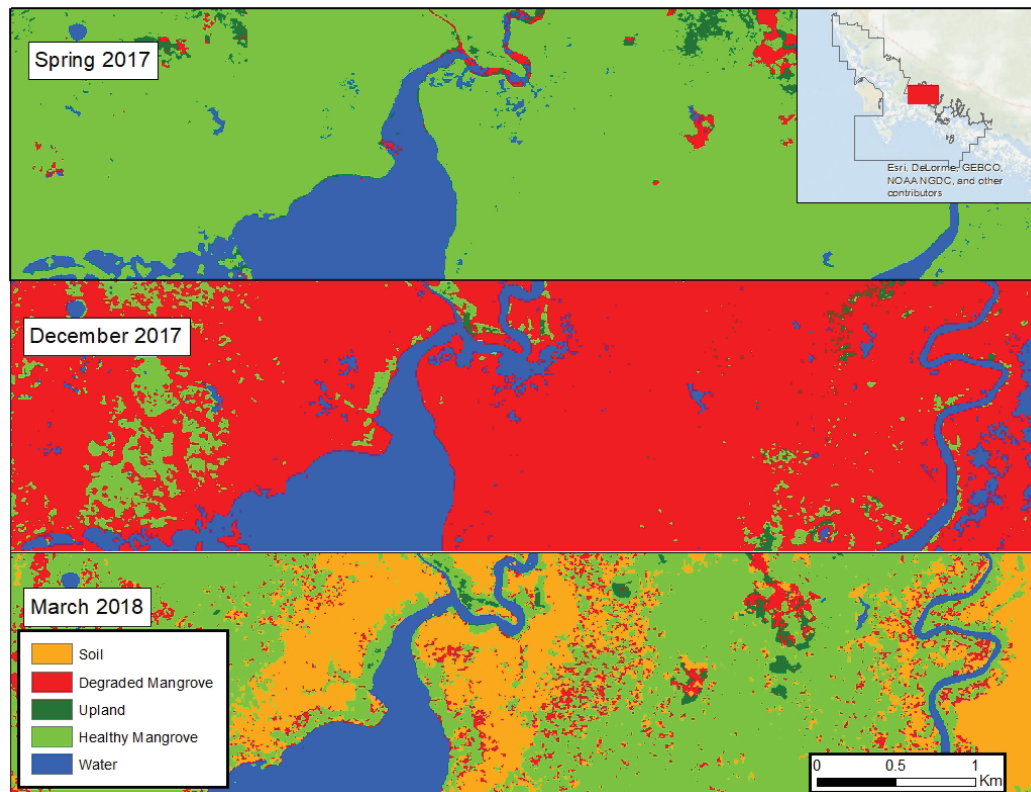


Figure 7.7. Time series of satellite-derived habitat types indicating healthy mangrove pre-Irma (top) that was damaged by the hurricane (center) and either recovered or died back to expose bare soil (bottom).

under which no mangroves were planted. Volunteer mangroves now colonize the site.

An additional 89 ha (221 ac) of stressed and dead mangroves are planned for restoration beginning in 2021, led by the FWC with Hurricane Irma recovery funds from NOAA. The restoration will replace a culvert with two 60-cm (2 ft) culverts and install another 60-cm culvert under San Marco Road. Monitoring reports and plan descriptions are available at <https://www.conservancy.org/>.

- Picayune Strand restoration project:** In 1996, SFWMD developed a conceptual plan for the hydrologic restoration of Picayune Strand State Forest. The forest was identified as essential habitat and in 1998 was incorporated in the effort to restore the western Everglades as part of CERP. The restoration efforts included the installation of pump stations, spreader channels, 133 km (83 mi) of canal plugs, and 365 km (227 mi) of road removal (<https://www.evergladesrestoration.gov/>). The Picayune Strand restoration project was designed to improve sheet flow, wetland quality, and ecological connectivity between adjacent state and federal conservation lands. A number of monitoring projects have been associated with the restoration, including vege-

tative, hydrologic, and wildlife assessments conducted by a variety of agencies (SFWMD, U.S. Army Corp of Engineers, USFWS, Rookery Bay NERR, CSF, Florida Gulf Coast University, and Audubon). See Chuirazzi and Duever (2008) for a summary and baseline data from the restoration project.

- Clam Bay Natural Resource Protection Area:** In 1999, Collier County initiated a 10-year, multiagency restoration project in Clam Bay estuary. Tidal flow was improved by dredging the main tidal creeks, clearing small tributaries, and hand-digging channels for draining excess surface water. Restoration and monitoring were initiated by Lewis Environmental Services Inc. and CSF and continued by CSF, EarthTech, and Turrell, Hall & Associates Inc.

Monitoring data indicated that restoration has increased tidal flushing and removed a substantial amount of standing freshwater from the areas with highest mortality, leading to natural revegetation (Worley and Schmid 2010). For the past two decades, Clam Bay has been subjected to multiple stressors, anthropogenic and natural, which have interrupted forest development and maturity. Unfortunately, in 2016, higher than normal rainfall during the dry season caused a

recurrence of extended periods of inundation, which caused stress and mortality within the system. The long-term viability of this system remains uncertain and depends largely on the degree of tidal flushing in the forest (Worley 2019). Monitoring will be continued to evaluate the long-term success of the restoration and health of the mangrove forest.

- **Windstar Country Club:** In 1982, restoration commenced on 6 ha (15 ac) of mangrove forest as mitigation for impacted wetlands (Lewis 1990, Peters 2001). Postmitigation monitoring was conducted from 1989 through 2000 to compare colonization, growth, and succession in the restored site with that in a natural mangrove forest (Proffitt and Devlin 2005). By 2000, species richness and vegetation cover in the created mangrove forest were similar to those in the natural forest, although the trees were smaller, with higher stem density, and black mangroves were less frequent.
- **Henderson Creek Mangrove Restoration:** Three hectares (7.4 ac) of mangrove forest, leveled and filled in 1973, were restored in 1991. One year of postrestoration monitoring found that fish and macroinvertebrate species in the restored site differed from those at an adjacent natural mangrove forest (Shirley 1992). In a longer-term monitoring study of Henderson Creek and the Windstar Country Club sites, McKee and Faulkner (2000) found that the ecosystem and biogeochemical functions of the restored sites varied widely depending on hydrology, salinity, and soil characteristics.

Recommendations for protection, management, and monitoring

- Prevent rapid stormwater runoff in the watershed. Extensive drainage canals and urban stormwater systems rapidly transport and concentrate stormwater rather than release it as a steady, continuous flow. Conversely, blockage of surface water flow due to roads or other impoundments can be just as harmful and result in stagnant water, vegetation death, and peat collapse. While hydrology cannot be fully restored due to human development, unneeded drainage canals can be filled to diffuse surface water, rehydrate dried wetlands, and reduce salinity in coastal wetlands (CSF 2011). Additionally, sustainable agricultural practices, enhanced wastewater treatment, and stormwater management are needed to reduce nutrient input and subsequent eutrophication of coastal estuaries.
- Complete a regional map to characterize conditions, prioritize restoration areas, and define monitoring

and management objectives for restoration in order to improve understanding and enhance management of coastal wetlands. Because of the range of participating organizations, an interagency working group could provide the best approach for developing and implementing a plan over the long term.

- Monitor vegetation and water quality to identify locations of stress and changes over time (FDEP 2012). Systematic long-term monitoring is critical to evaluating the success of restoration projects, developing management models to identify areas of stress, and predicting recovery as a result of restoration actions. Unfortunately, due to limited funding, most monitoring has been limited to specific hurricanes or individual projects. 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 and countries in the global effort to maintain and regain coastal mangrove forests.

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- NASA G-LiHT image database
<https://glihtdata.gsfc.nasa.gov/>
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