Chapter 9

Florida Keys

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Description of the region

The Florida Keys (Figure 9.1) are a 210-km-long (130 mi) archipelago on the southern edge of the Florida carbonate platform (Perkins 1977, FKNMS 2007). The islands are composed of Miami oolite and Key Largo limestone, which formed during the last interglacial period of the Pleistocene epoch (Hoffmeister and Multer 1968, Perkins 1977). Prevalent sediment types include rocky and organic soils, calcareous muds, and carbonate sands (Hurt et al. 1995). The highest elevation in the Keys is approximately 5.5 m (18 ft), but most of the islands do not extend higher than 2 m (6.6 ft) above sea level (Ross et al. 1992). Native American burial grounds and middens can be found in parts of the Keys and contribute to some local elevation (Goggin 1944).

Although a railroad to Key West was constructed in the early 1900s, the Keys had relatively low development until the completion of U.S. Highway 1 in the 1930s (Hurt et al. 1995). Today, tourism drives the economy, particularly for marine activities such as diving, snorkeling, and charter and recreational fishing (FKNMS 2007). The population of Monroe County, which includes the Keys and the western half of the Everglades, is still relatively small, in 2019 estimated at 74,000 (U.S. Census 2019).

The archipelago is encompassed by the Florida Keys National Marine Sanctuary. Within this extent, the many protected regions include Dry Tortugas National Park (not included in Figure 9.1 due to a lack of land-use/land-cover data), Key West National Wildlife Refuge (NWR), Great White Heron NWR, National Key Deer Refuge, and Crocodile Lake NWR. Additionally, approximately 5,260 ha (13,000 ac) of land acquired through various conservation efforts are managed by the Florida Fish and Wildlife Conservation Commission (FWC), Florida Department of Environmental Protection (FDEP), local governments, municipalities, and nongovernmental conservation organizations. The FWC Florida Keys Wildlife and Environmental Area, Dagny Johnson Key Largo Hammock Botanical State Park, John Pennekamp Coral Reef State Park, and several other Keys state parks contain large areas of protected habitat. The acreage of protected land is projected to increase as purchases are made through the FDEP's Florida Forever program and the Monroe County Land Authority.

Red mangrove (*Rhizophora mangle*) lines approximately 2,900 km (1,800 mi) of shoreline in the Florida Keys National Marine Sanctuary (FKNMS 2007). Black mangrove (*Avicennia germinans*) and white mangrove (*Laguncularia racemosa*) are also found throughout the Keys, often scattered among intertidal marshes (USFWS 1999a). Freshwater and nontidal wetlands also include many mangrove and buttonwood (*Conocarpus erectus*) trees interspersed in the sawgrass (*Cladium jamaicense*) marshes (USFWS 1999a). Dwarf mangroves with heights of 1–3 m (3.3–10 ft) are common as a result of limited nutrients, rocky substrates, and soils with low organic matter (Hurt et al. 1995, USFWS 1999b). In organic soil in the Keys, mangroves reach heights of 3–6 m (10–20 ft) or more (Ross et al. 1994, Hurt et al. 1995).

Salt marshes are also found, to a lesser extent than mangroves, in the Lower Keys (Figure 9.1). Herbaceous plants are often mixed in with scrub mangroves and buttonwood trees. Gulf cordgrass (*Spartina spartinae*) dominates, but other Spartina species include smooth cordgrass (*S. alterniflora*), sand cordgrass (*S. bakeri*), and saltmeadow cordgrass (*S. patens*) (Ross et al. 1992, Klett et al. 2006). Other salt-tolerant vegetation includes

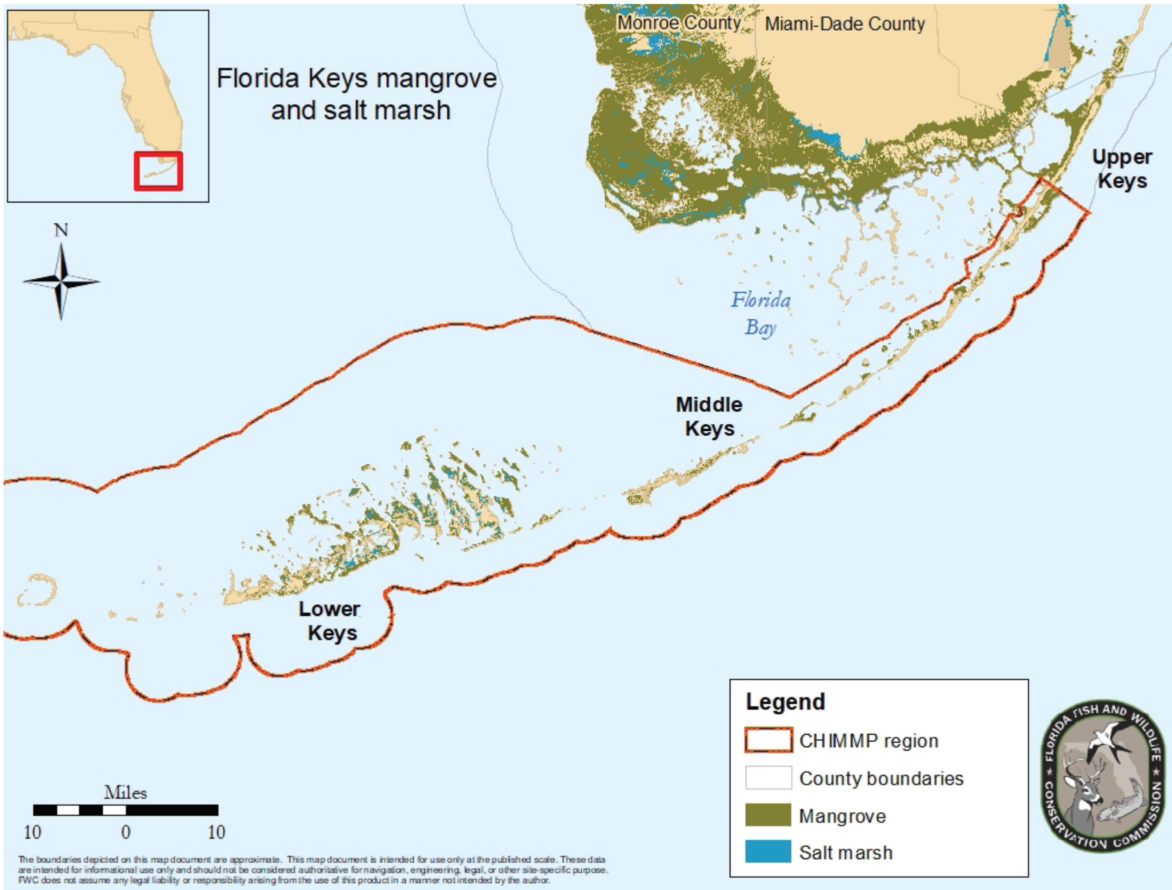

Figure 9.1. Mangrove and salt marsh coverage in the Florida Keys. Data source: SFWMD 2014–2016 land-use/land-cover data, based on FLUCCS classifications (FDOT 1999, SFWMD 2018).

saltgrass (*Distichlis spicata*), shoregrass (*Monanthochloe littoralis*), seashore dropseed (*Sporobolus virginicus*), marsh fimbry (*Fimbristylis spadicea*), and saltwort (*Batis maritima*) (FNAI 2010). Wetland subtypes include open scrub salt marsh and buttonwood-dominated scrub salt marsh (USFWS 2009).

Many coastal wetlands in the Florida Keys were ditched, filled in, or fragmented in mosquito-control operations or in dredge-and-fill construction of canals and neighborhoods (FKNMS 2007, TNC 2009). This wetland fragmentation decreased mangrove forest size and increased the edge-to-area ratio (Strong and Bancroft 1994). As of 1994, 15% of mangrove forests in the Upper Keys (Figure 9.1) had been cleared for development; losses were particularly high for areas close to major roads (Strong and Bancroft 1994). Loss of coastal wetlands in the Keys has contributed to local problems with polluted surface runoff entering coastal waters (FKNMS 2002).

A number of powerful hurricanes passed directly over the Florida Keys during the past 100 years, including unnamed hurricanes in 1929, 1935, and 1948, Hurricane Donna in 1960, Inez in 1966, Floyd in 1987, and Irene in 1999 (NOAA 2019). More recently, Irma made landfall at Cudjoe Key in the Lower Florida Keys in September 2017 with maximum winds of 213 km hr^{-1} (132 mph; Canglialosi et al. 2018). Storm surge and high tide caused inundation levels as high as 1.5–2.4 m (5–8 ft) in the Lower Florida Keys. Irma devastated many of the mangrove forests, particularly tall forests, which received the brunt of the high-force winds. Many of the mangrove seedlings and scrubs were protected from wind damage by submersion beneath the storm surge (Figure 9.2). Recovery has been slow, particularly for forests that experienced delayed mortality associated with the storm surge deposits (Radabaugh et al. 2020). Although these storm surge deposits can cause mortality in mangroves, they also are an important source of nutrients and substrate to the forest, helping the rate of forest floor accretion keep pace with sea-level rise (Castañeda-Moya et al. 2010, 2020). Hurricane Irma also exacerbated stress on mangrove forests that were already suffering from restricted tidal flow due to roads or other coastal development.

Hurricane Irma pushed massive amounts of marine debris into mangrove forests, including derelict boats,

Figure 9.2. Examples of extensive damage to a tall mangrove forest (left) and minimal damage to a scrub mangrove forest (right) in the Lower Florida Keys two months after Hurricane Irma (2017). Photo credits: Kara Radabaugh.

lobster traps, ropes, buoys, and miscellaneous wooden, plastic, foam, and fiberglass debris (SNC-Lavalin and Atkins 2018). Chemicals from fuel and oil tanks, batteries, and electronics also spilled or leached into the water during the hurricane and after the storm as derelict vessels disintegrated over time. Removal of marine debris is often costly and labor-intensive (SNC-Lavalin and Atkins 2018).

The low elevation of the Florida Keys makes them highly vulnerable to storm surge and sea-level rise. Upland forests of the Lower Keys have already lost many pine trees due to storms and saltwater intrusion (Ross et al. 2009, 2020). Even under an optimistic scenario of sea-level rise (i.e., 0.35 m/1.15 ft by 2100), models by The Nature Conservancy (TNC) predict that 31% of Big Pine Key will be inundated by 2100. Under a less optimistic scenario (1.4 m/4.6 ft of sea-level rise by 2100), 96% of the island would be under water (TNC 2009).

In the short term, mangroves are one of the few ecosystems in the Keys that appear to be benefiting from sea-level rise (Glazer 2013). In many areas, mangroves have already encroached on salt marshes and upland ecosystems. Between 1935 and 1991, mangrove extent on Sugarloaf Key increased by 47%, while upland extent decreased by 31% (Ross et al. 1992, 2009). Upland forest and freshwater ecosystems can transition rapidly to mangroves, due to the effects of even a single storm surge (Ross et al. 2009). Comparison of aerial photographs representing a span of about 60 years also shows the dramatic increase in red mangrove forests as they expand in many areas of the Keys (Kruer, unpubl. data; Zhai et al. 2019). While inland mangrove expansion is common throughout Florida, mangrove forests in the Florida Keys have also expanded into shallow seagrass flats, creating new mangrove islands or expanding mangrove fringe. The example of mangrove expansion onto the flood-tidal delta in Figure 9.3 may be linked with local sediment accumulation. A similar trend of mangrove expansion inland and into adjacent shallow waters has also been noted on islands in Florida Bay (Zhai et al. 2019). Although the expansion in available habitat is beneficial for mangrove-dependent species, it results in the concurrent loss of seagrass, salt marsh, or upland vegetation (Zhai et al. 2019).

Mangroves also occur to a limited extent in Dry Tortugas National Park, although historical accounts note that mangroves are periodically killed by hurricanes (Doyle et al. 2002). Mangroves that survive there today face challenging conditions, including erosion, an excess of pelican guano, a lack of freshwater, and low organic-matter content in the sediment on the coral islands (Doyle et al. 2002). The presence of all three mangrove species indicate the successful colonization of drifting propagules.

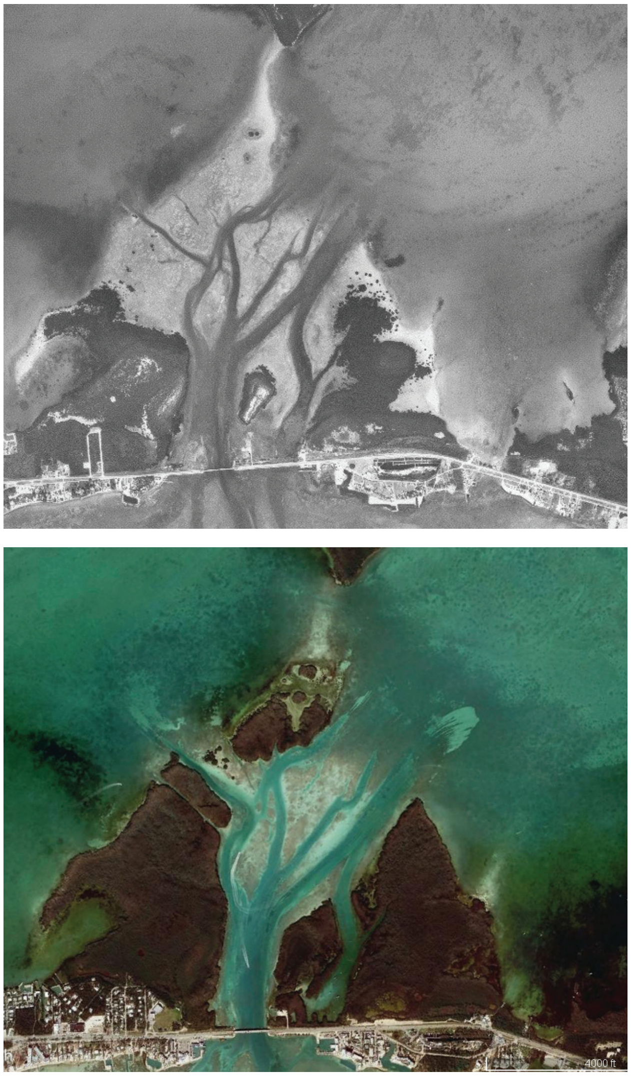

Figure 9.3. Mangrove expansion in Whale Harbor on Islamorada; aerial images from 1955 (top) and 2017 (bottom). Mangrove expansion is evident both inland and into shallow waters of the flood-tidal delta of the Whale Harbor inlet. Photo credits: U.S. Coast and Geodetic Survey (top) and Google Earth (bottom).

Threats to coastal wetlands

- **Climate change and sea-level rise:** Low elevation and small land area render terrestrial ecosystems in the Florida Keys highly vulnerable to sea-level rise and storm surges. While upland habitats are the most vulnerable, salt marshes also face steep declines in the face of rising sea levels as they are inundated or are overtaken by mangrove forests (Clough 2008). Mangrove area is expected to continue expanding in the short term at the expense of adjacent native vegetation. Some regions, such as Crocodile Lake NWR, lack room for landward expansion of mangroves due to higher inland elevation and will likely experience declines in mangrove extent this century (Clough and Larson 2010). If sea-level rise progresses to 1.5 m (4.9 ft) or more by 2100, mangrove extent is projected to eventually decline in other Florida Keys regions as well (Clough 2008).
- **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). Additionally, marine sediments deposited by storm surges can lead to mangrove mortality if they bury lenticels on the trees' aerial roots (Ellison 1998, Radabaugh et al. 2020); however, storm surges are an important source of nutrients and substrate for mangrove forests (Castañeda-Moya et al. 2010, 2020). Saline floodwaters that become impounded by anthropogenic barriers or storm-transported sediments can also cause stress and mortality (Krauss and Osland 2019).
- **Invasive species:** Several invasive species are already altering natural Florida Keys coastal communities. They include Australian pines (*Casuarina* spp.), Brazilian pepper (*Schinus terebinthifolia*), and latherleaf (*Colubrina asiatica*) (Hadden et al. 2005, USFWS 2009). The Florida Keys Invasive Exotics Task Force is a multiagency group that focuses on the control and removal of invasive plants (TNC et al. 2019), but removal of invasive species from publicly managed lands is made more difficult by the proximity of private lands that are often landscaped with nonnative plants.
- **Urban development:** Dredge-and-fill operations have already removed large areas of coastal wetlands in the Keys. Human development also impacts remaining mangroves and salt marshes through altered hydrology. Increased impervious surfaces and ditches alter the flow of freshwater, already in short supply because the land area available for retaining precipitation is small. A decline in coastal wetlands surrounding centers of urban development also has significant impacts on the quality of surrounding coastal waters. Without coastal wetlands to provide a natural filter, pollution from stormwater runs off directly into the ocean (FKNMS 2002).
- **Herbivory:** Federal protection and the establishment of the National Key Deer Refuge have allowed the population of the endemic Key deer (*Odocoileus virginianus clavium*) on Big Pine and No Name keys to rebound from only 25–50 animals in the late 1940s to an estimated population of 1,000 in the early 2000s (Lopez et al. 2004, Barrett and Stiling 2006, Hoffman 2015). This population, however, was estimated to have declined

20–40% after Hurricane Irma (Parker et al. 2018). Key deer are selective grazers; as a result, the abundance of the woody species the deer prefer is lower on islands with high deer populations (Barrett and Stiling 2006). The density of small (< 1.2 m/4 ft) red mangrove trees was lower and foliage had been stripped from red mangroves in areas with a high deer density (Barrett 2004). While the threats of herbivory may not be as great a threat to Florida Keys vegetation as are sea-level rise and urbanization, the impacts of the Key deer highlight the need for ecosystem-level management in the Keys.

Mapping and monitoring efforts

Water management district mapping

The South Florida Water Management District (SFWMD) conducts regular land-use/land-cover (LULC) surveys in the district every 3–5 years. Figure 9.1 shows the 2014–2016 LULC map (SFWMD 2018), which was the most recent SFWMD LULC map of the Florida Keys available at publication. Land-cover classifications were based on SFWMD modifications to the 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 maps (Figure 9.1) were made by interpreting aerial photography and updating 2008–2009 vector data.

Cooperative Land Cover mapping

The statewide Cooperative Land Cover (CLC) maps are created as a collaboration between the Florida Fish and Wildlife Conservation Commission (FWC) and the Florida Natural Areas Inventory (FNAI). CLC maps draw from a variety of mapping sources, including water management district LULC maps, but follow a modified land-cover-classification scheme (Kawula and Redner

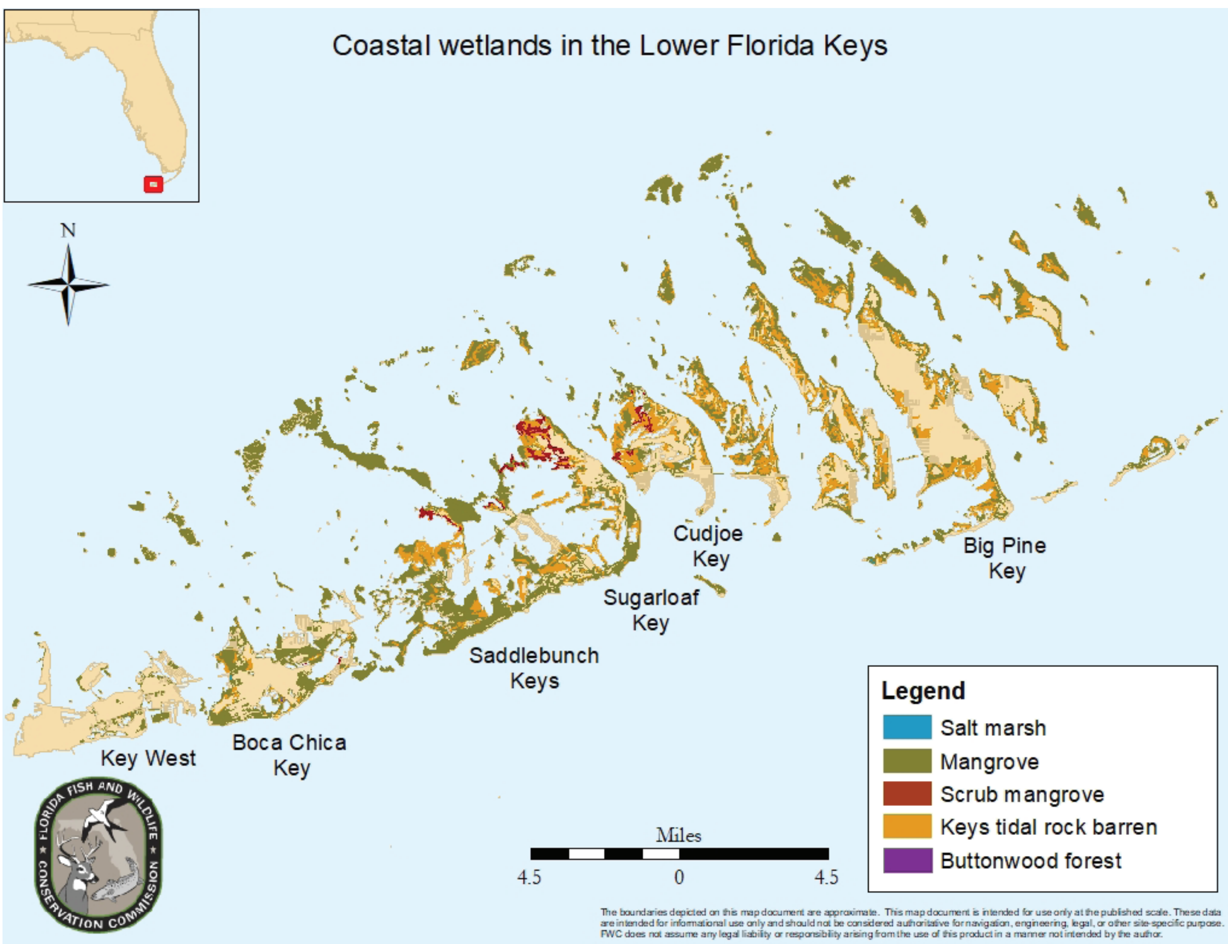

Figure 9.4. Coastal wetland extent in the Lower Florida Keys, as determined by Cooperative Land Cover Map (CLC) version 3.3, following the Florida Land Cover Classification System (FNAI 2010, FNAI and FWC 2018, Kawula and Redner 2018). Within this extent, CLC identifies salt marsh and buttonwood forest only in very small areas on Boca Chica Key.

2018). In addition to the categories of mangrove and salt marsh, CLC maps add categories for scrub mangroves, buttonwood forest, and Keys tidal rock barren (Figure 9.4). Keys tidal rock barren describes areas of generally succulent species and stunted mangroves on exposed limestone; this land-cover type occurs only in the Florida Keys (FNAI 2010, Kawula and Redner 2018).

Local land-cover mapping

- **Florida Keys wetland mapping:** Wetlands (along with upland ecosystems) were mapped in the late 1980s on 19 islands in the Lower Keys in known Key deer habitat as part of Key deer habitat management efforts (Folk et al. 1991). This detailed mapping included transects in all ecosystems on all islands and the mapping and monitoring of more than 1,000 freshwater and nontidal wetlands. Keys wetlands were also mapped for the U.S. Environmental Protection Agency's Florida Keys Advance Identification Project (Kruer 1995). Mapped wetland communities included mangroves, salt marshes, and buttonwood wetlands, along with nontidal wetlands (freshwater sloughs, freshwater basins, and impounded wetlands) that frequently included mangroves and other salt-tolerant vegetation (Kruer 1995).
- **Land-cover change analysis for Big Pine Key (1959–2006):** Using a combination of digital elevation models, canopy-height models, and high-resolution aerial photography (Hudson 2006), Zhang et al. (2010) delineated land-cover community types on eight islands in the lower Florida Keys from Sugarloaf Key to Little Pine Key based on the Keys ecological site classification system of Ross et al. (1992). Mangrove classes, which included both red and black mangrove forests and dwarf mangrove mudflats, accounted for 28% of land cover on Big Pine Key and the majority of land cover (55%) on Sugarloaf Key. An assessment of change over nearly 50 years was conducted for Big Pine Key by comparing the 2010 product to the same land cover categories classified using black-and-white aerial photographs from 1959. On Big Pine Key, an increase of 114 ha (282 acres; a 62% increase) of mangrove forest was documented from 1959 to 2006, but 89 ha (219 ac) of dwarf mangrove mudflat was lost (a 16% decrease) as these areas were colonized by mangroves.
- **Monroe County mapping:** In 2009, Photo Science Inc. completed land-use/land-cover mapping of the Florida Keys for Monroe County (Photo Science 2009). The maps were created from high-resolution orthophotographs with a minimum mapping unit of 0.2 ha (0.5 ac) for all classifications except hammocks, for which the minimum mapping unit was 0.14 ha (0.35 ac). Classification categories included scrub mangrove (dwarf mangroves shorter than 1.5 m/5 ft), buttonwood, mangrove, and salt marsh.

Sea Level Affecting Marshes Model in the Florida Keys

The Sea Level Affecting Marshes Model (SLAMM) has been used to model various scenarios of the impact of sea-level rise on the Florida Keys (Clough 2008, Clough and Larson 2010, Glazer 2013). The study predicted that mangroves would continue to increase in acreage at the expense of higher-elevation habitats and thus that mangrove-dependent species could initially benefit from sea-level rise (Glazer 2013). In the National Key Deer Refuge, mangrove extent is predicted to increase under all but the most extreme scenarios. The extent of salt marsh, transitional salt marsh, and brackish marsh are all expected to decline under all sea-level-rise scenarios (Clough 2008). In Crocodile Lake NWR on North Key Largo, mangroves and tidal swamps are predicted to decline under all scenarios (Clough and Larson 2010), because the narrow barrier island with relatively high elevation uplands offers little area for retreat, and the extensive mangrove forests lining the bay will be lost and overtaken by open water.

Monitoring hurricane damage and recovery

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

- **FWC monitoring:** Damage and early recovery following Hurricane Irma were monitored by the FWC Fish and Wildlife Research Institute from 2017 through 2019. Vegetation monitoring on several backcountry islands in the Lower Florida Keys included quantification of tree mortality, soil shear strength, root growth rates, canopy recovery, and understory development (Radabaugh et al. 2020). Mangrove mortality varied widely depending on the height of the trees and protection from wind. Some forests suffered almost total mortality, while other forests, with smaller trees submerged by the storm surge, experienced minimal damage (Figure 9.2). Some mangroves that initially survived the hurricane died several months later; this delayed mortality was linked to thickness of the carbonate-mud storm surge deposit on the forest floor. Additional monitoring focused on the thinning, transformation, and microbiota of this storm surge deposit over time.

- **Monitoring hurricane impacts via remote sensing:** Scientists from Ocean Imaging Corp and Florida International University monitored impact and recovery from Hurricane Irma using a time series of 10-m-resolution (3.3 ft) Sentinel satellite images across eight islands in the lower Florida Keys (Sugarloaf to Little Pine Key), over which the eye of Hurricane Irma passed in September 2017 (Svejkovsky et al. 2020). The normalized difference vegetation index (NDVI) was used to detect changes in vegetation canopy cover by comparing data from a prestorm image (from October 2016) to a series of poststorm images (from October 2017 to May 2019). The greatest immediate decreases in NDVI (between October 2016 and October 2017) were observed in mangrove forests located east of the path of Irma's eye wall from Big Pine Key to Little Pine Key. Continued decreases in NDVI were noted into January 2018. Recovery of NDVI, and by extension, canopy cover, was not observed in red mangrove forests, while some minimal recovery was observed in black mangrove forests. However, much of the NDVI recovery in black mangrove forests appeared related to growth of herbaceous halophytes like saltwort and was not attributable to mangrove recruitment or sprouting.
- **Valuing flood risk reduction from mangroves:** Scientists with The Nature Conservancy, University of California Santa Cruz, and Risk Management Solutions Inc. calculated property damage in south Florida caused by storm surge during Hurricane Irma with and without the protection of mangrove forests (Narayan et al. 2019). The study showed that mangroves reduced damages due to the storm surge by $11 million in the Florida Keys due to their ability to stabilize shoreline and reduce the height of storm surge. This equated to a risk reduction of $700 ha^{-1} ($280 ac^{-1}) in the Keys. Across south Florida, mangroves prevented an estimated $1.5 billion in property damages during Hurricane Irma. Wider swaths of mangrove forests were found to provide the greatest protection, but even narrow forests provided significant protection to property (Narayan et al. 2019).

Recommendations for protection, management, and monitoring

- Target specific areas for preservation that represent all local ecosystems, are most likely to survive sea-level rise, and are sufficiently connected with other habitats to allow gene flow among organism populations (Ross et al. 2009). Given that sea-level rise is one of the primary threats to native ecosystems in the Florida Keys, the causes of climate change should be targeted, coupled with management and restoration to create more resilient natural areas (TNC 2009).
- More rigorously monitor, manage, and restore freshwater and nontidal resources because they are critically important to wildlife including many listed species and migratory birds. Wetland restoration plans should take into account present and future freshwater resources with regards to saltwater intrusion and modifications of surface hydrology resulting from human development.
- Continue successful programs that restore, protect, and enhance both tidal and nontidal wetlands throughout the Keys (FWC 2004, Hobbs et al. 2006). Continue to purchase strategic land to conserve Florida Keys habitat against human development (FWC 2004). Habitat connectivity, long-term resilience, and freshwater resources are key considerations for land purchases.
- Complete the mapping and monitoring of wetland and adjacent upland vegetation to assist in quantifying habitat shifts. Data on mangrove density as well as cover would be beneficial, because density is not being widely recorded or mapped, which hampers observing and quantifying changes in forest structure.
- Florida Keys NWR management plans often recommend the filling of some mosquito ditches and unnecessary canals because they alter hydrology and often result in stagnant water (Klett et al. 2006, USFWS 2009). Decisions regarding ditch restoration should be made case by case and incorporate projections of sea-level rise and freshwater flow as well as mosquito control considerations. Ditch filling may be most beneficial for ditches which allowed saltwater intrusion into historically nontidal wetlands (some of which are now dominated by red and white mangroves). Some ditches are now important sources of freshwater to resident plants and animals. Thus, the preservation and enhancement of scarce freshwater resources should be considered before undertaking wetland restoration. Location-specific research is needed to determine whether ditch filling would in fact be beneficial for surrounding ecosystems.
- Management objectives of the Florida Keys National Marine Sanctuary, the NWRs in the Lower Florida Keys, state-managed lands, Monroe County, and municipalities often emphasize the importance of combat-

ing invasive vegetation to protect mangrove and other coastal wetland habitats (FKNMS 2002, FWC 2004, TNC 2009, USFWS 2009, TNC et al. 2019). Mapping and monitoring of the extent of invasive vegetation is critical to assessing effectiveness and optimizing efforts (FWC 2004, Hobbs et al. 2006).

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