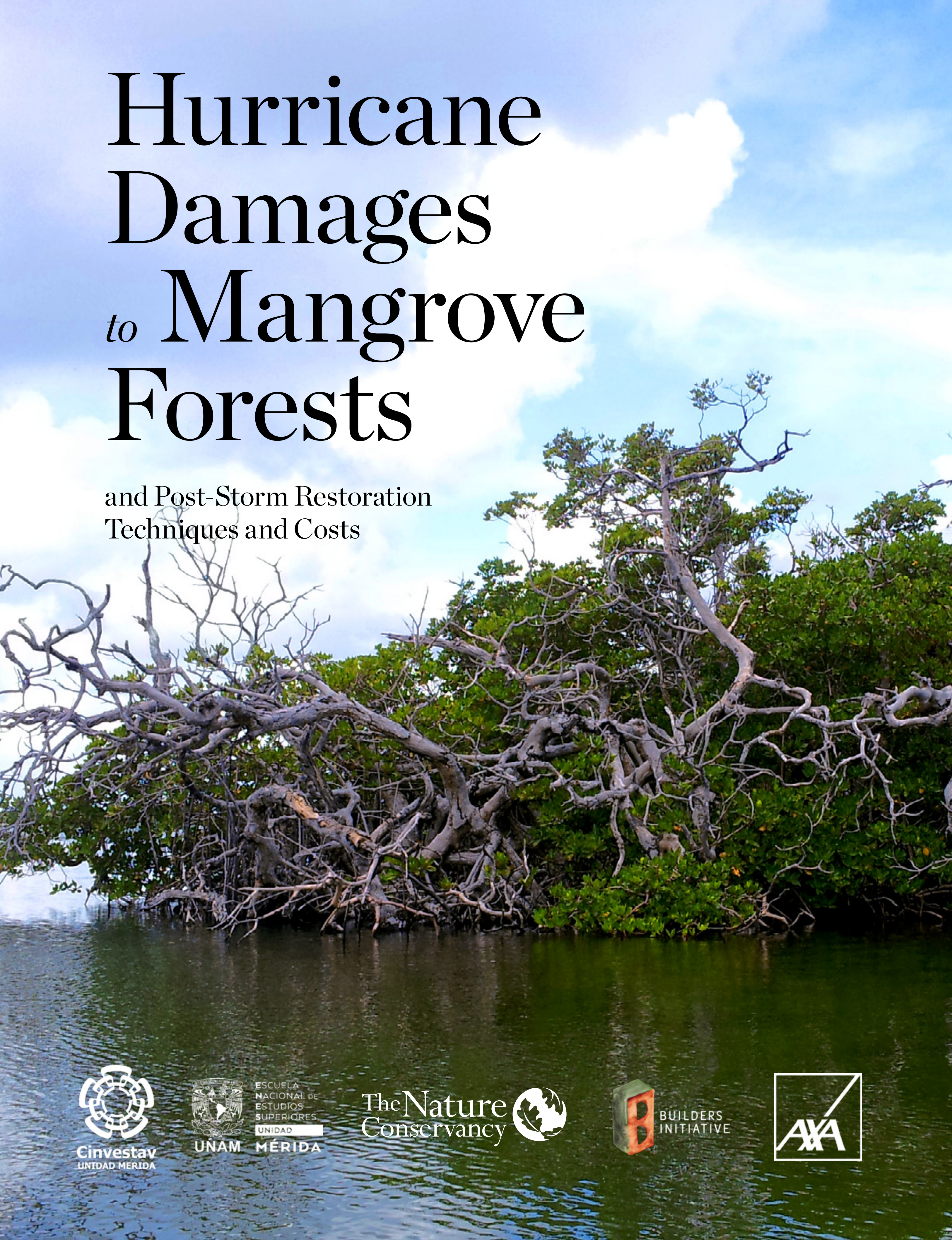
Hurricane Damages *to* Mangrove Forests

and Post-Storm Restoration Techniques and Costs



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Builders Initiative
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Hurricane Damages to Mangrove Forests and Post-Storm Restoration Techniques and Costs

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Photograph on the cover: Defoliation and damages to mangrove structures in Sian Ka'an, Mexico following Hurricane Ernesto.

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This report is the first of three reports to be released by TNC in collaboration with our partners at AXA XL, CINVESTAV, and the University of California, Santa Cruz. The reports are part of a year-long project aimed at assessing the feasibility for a mangrove insurance project in the Gulf of Mexico and Caribbean. In this first report, we document the types of mangrove damages that may result from hurricanes, the appropriate restoration techniques to adequately restore damaged mangroves, and the costs of these restoration efforts. In the second report, we document the protective value of mangrove forests in the study region. Finally, in the third report we aggregate information from the first two reports and identify specific areas where a mangrove insurance product would be most cost-effective. We also summarize the efforts of our market analysis in Mexico, Florida and The Bahamas and identify specific locations where a mangrove insurance product could be piloted. As described in this report, tropical storms and hurricanes can cause significant damages to mangroves and restoration costs can be high. Financing these restoration activities, through innovative solutions like an insurance product, will be critical to ensuring that the protective benefits of mangroves are sustained in the future.

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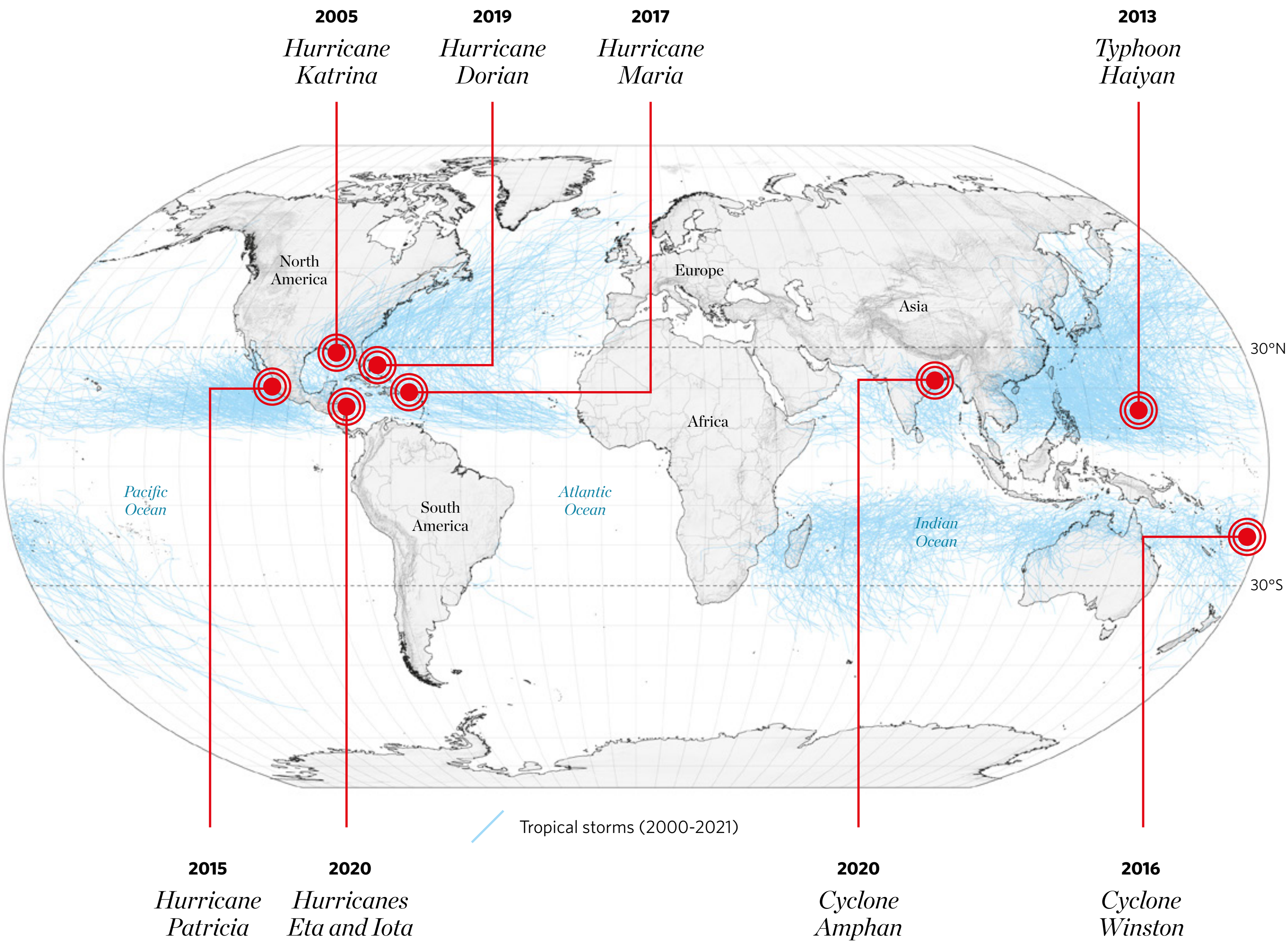
1 Introduction

Mangroves in Alligator Creek, Cat Island, Bahamas. © Shane Gross.

Mangrove forests provide important ecosystem services, such as habitat for fish and crustaceans, water filtration, carbon sequestration, soil formation and protection against coastal erosion through soil stabilization, sediment accumulation and amelioration of storm surge (Cohen-Shacham *et al.*, 2016; Herr and Landis, 2016; IUCN, 2020).

Protection against tropical cyclones, which can be called typhoons or hurricanes depending on where they occur in the world, is one of the most beneficial environmental services provided by mangroves to human settlements near the coast. It is estimated that approximately two-thirds of the world's human population lives within 40 miles of the coast, which are highly vulnerable to tropical cyclones (UN Atlas of the Oceans, 2016). Recent research shows that mangrove forests dissipate wave energy and slow storm surge penetration, which can lower flood damage and minimize erosion (World Bank, 2016). Globally, mangroves provide coastal protection services that avert $65 billion USD in damages and flooding for more than 15 million people each year (Menéndez *et al.*, 2020).

Around the world, there are numerous examples of coastal communities that have been devastated by these storm events (see Figure 1). In 2004, an Indian Ocean tsunami caused major damage to infrastructure and the death of more than 200,000 people (Check, 2005; Danielsen *et al.*, 2005). Hurricane Katrina devastated the United States' Gulf of Mexico coastline in 2005 and was considered the most expensive hurricane to date (Costanza *et al.*, 2006;



Day *et al.*, 2007). Typhoon Haiyan in 2013 was among the deadliest typhoons to hit the Philippines.

The degradation and loss of mangrove ecosystems as a result of deforestation and Earth's changing climate has decreased their ability to provide these ecosystem services (MEA, 2005; Costanza *et al.*, 2014; Zhao *et al.*, 2016). Moreover, mangroves can suffer great damage from tropical cyclones (Uriarte *et al.*, 2019), which further limits their capacity to provide these ecosystem services. Larger economic losses have been reported as mangroves degrade and coastal protection is compromised (Pendleton *et al.*, 2012). In addition to mangrove degradation, coastal erosion and rising mean sea level have exacerbated the impact of tropical cyclones (Nicholls and Casenave, 2010).

In this report, we characterize the damages caused by tropical cyclones to mangroves and recommend actions to reduce or repair damages to the mangroves. Although we focus on post-storm restoration activities for damaged mangroves, many of the mangrove restoration actions described can be applied in other settings. We describe the range of costs to repair mangroves in three priority regions: Mexico, Florida, and The Bahamas. Mangrove restoration in these three regions has previously been shown to be highly cost-effective (Beck *et al.*, 2020).

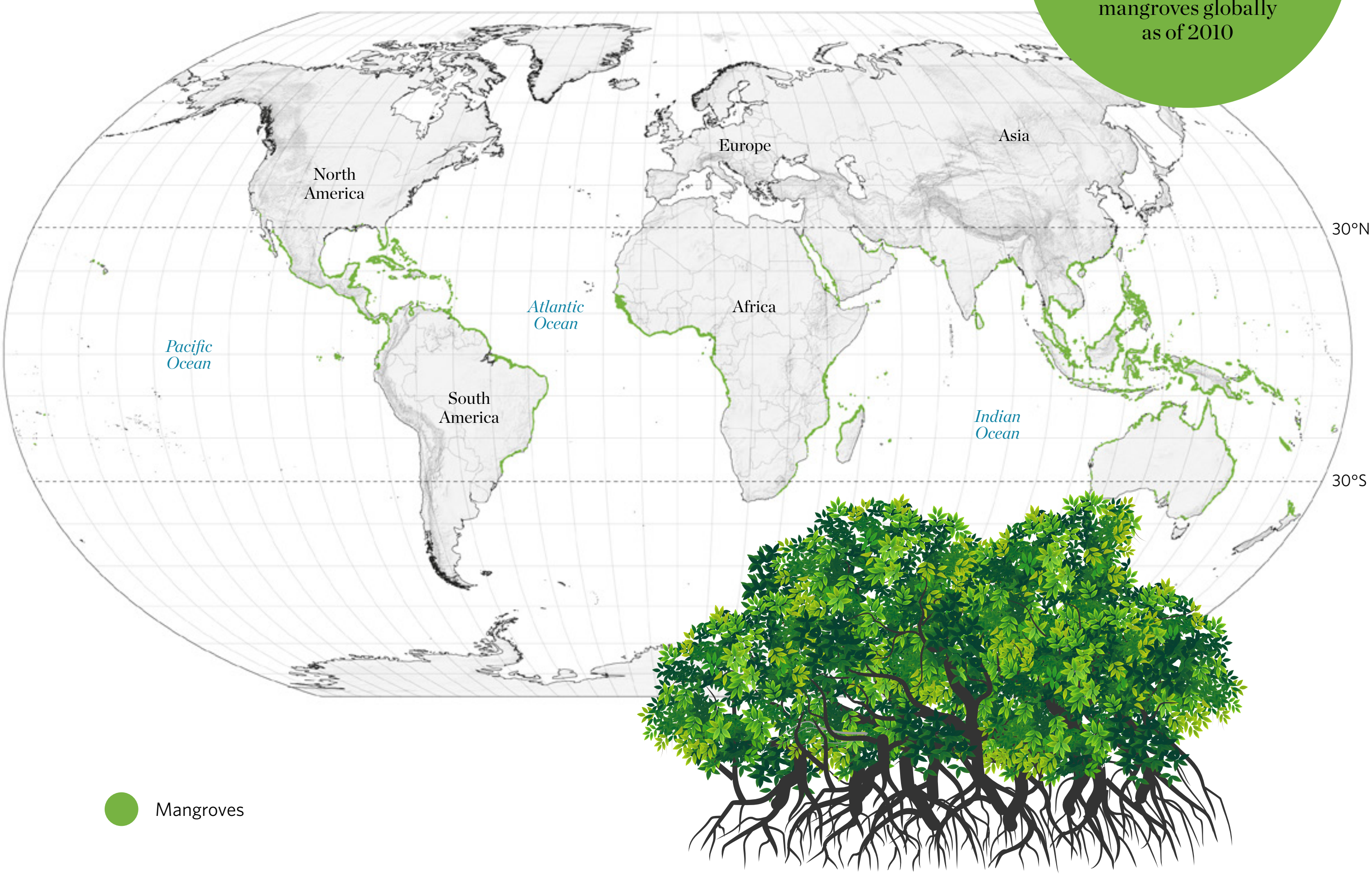
Figure 1. Track of tropical cyclones and historic storm events.

Note: Graphic includes tropical cyclone and hurricane tracks globally from 2000 to 2021.

Source: NOAA's International Best Track Archive for Climate Stewardship (IBTrACS) data, accessed on January, 2022. Made with Natural Earth.

Mangrove ecosystems

13.8
million hectares of mangroves globally as of 2010



Mangroves are distributed in the intertidal zone, along tropical and subtropical coasts, between 30° N and 30° S latitude (Giri *et al.,* 2011); about 75% of the world's mangroves are found in only 15 countries. The global coverage of these ecosystems is estimated at 13.8 million hectares (see Figure 2), however, deforestation of land for agriculture, aquaculture, urban settlements and hotel or port infrastructure and changes in climatic and environmental processes (Thomas *et al.*, 2017) are rapidly degrading and destroying mangroves. Since 1980, more than 3.6 million hectares of mangroves have been lost, accounting for more than 20% of the global mangrove coverage (FAO, 2007).

In 2010, due to the alarming rate of loss, the International Union for Conservation of Nature (IUCN) added 11 of the world's 70 mangrove species to the Red List of Threatened Species, and six as Vulnerable Species (FAO, 2007; Polidoro *et al.,* 2010). The condition of a mangrove forest and extent of loss is strongly related to the incidence of extreme weather events (intense storms, tropical cyclones, or tsunamis), oceanic processes (changes in mean sea level or climate of marine circulations) (Gilman, Ellison, Duke and Field, 2008), and a variety of human activities.

Figure 2. Global distribution of mangroves as of 2010.

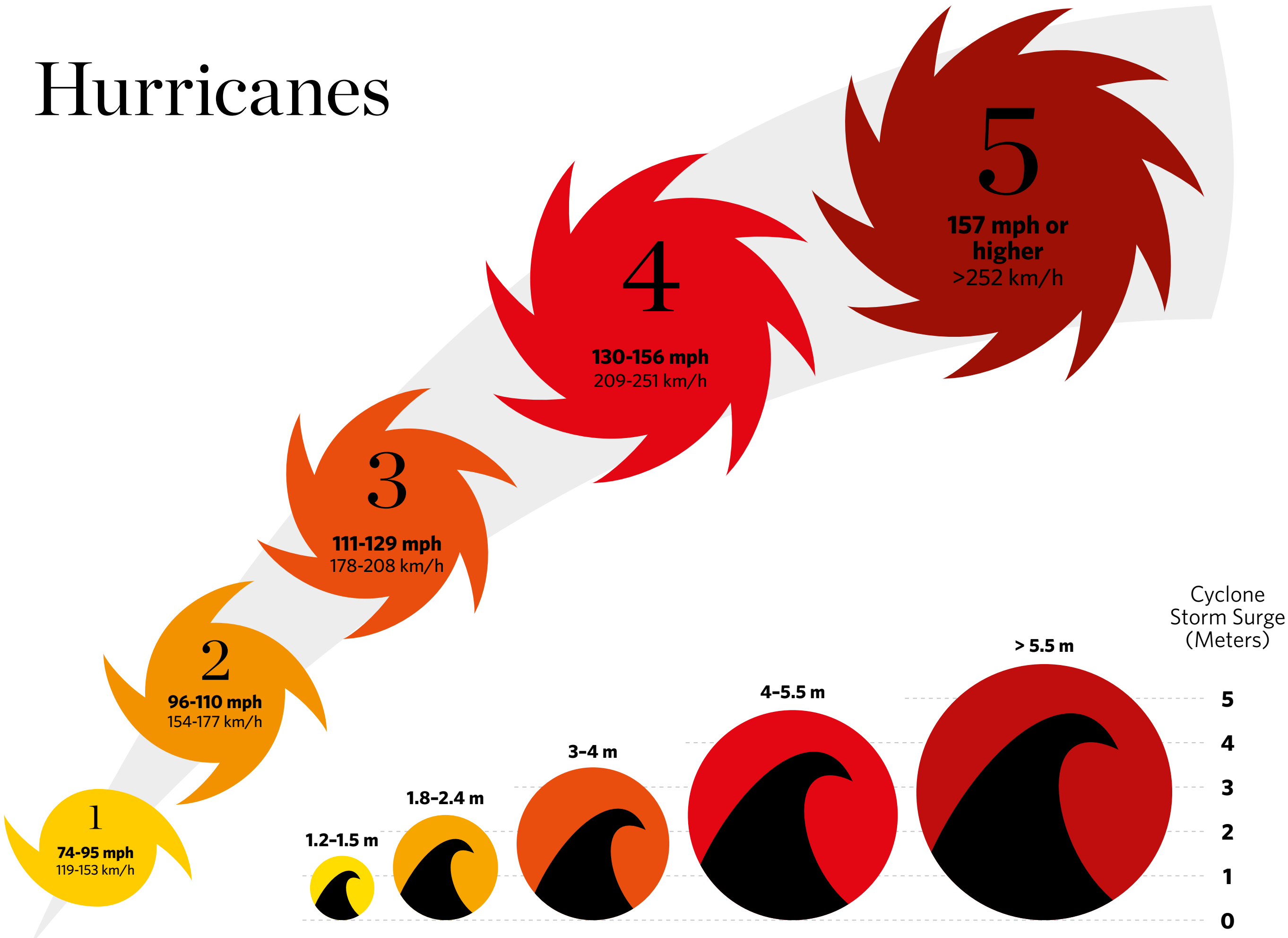
Source: Global Mangrove Partnership Dataset, World Atlas of Mangroves (Spalding, 2010). Made with Natural Earth.

Mangroves are traditionally located in areas exposed to disturbances (Lugo *et al.*, 1981); therefore, they are considered ecologically stable communities (Alongi, 2008) with the capacity to recover from damages caused by tropical cyclones. The frequency and magnitude of tropical cyclones plays a role in determining the composition and structural complexity of a mangrove forest. For example, in places where the tropical cyclone season is especially intense, the structural complexity of mangroves is characterized by shorter trees and few emergent taller trees (Lugo and Snedaker, 1974), whereas in areas where tropical cyclones are less frequent (some Pacific islands and Central America's Pacific coasts), structural biomass and complexity increases over time (Allen *et al.*, 2001; Simard *et al.*, 2019).

The characteristics of mangrove forests reflect the effect and recovery of previous disturbances and, in turn, influence the extent of the impact and the ecosystem response to future disturbances (Peters *et al.*, 2011). Tropical cyclones could potentially have greater impact on populated areas (Vogt *et al.*, 2012; Lewis *et al.*, 2016) where mangrove forests have been degraded or destroyed as a result of human activities.

Oysters grow on the mangrove coastline of Charlotte Harbor Estuary near Punta Gorda, Florida located on the Gulf of Mexico. © Carlton Ward Jr.

Hurricanes



Tropical cyclones are natural phenomena that typically develop in warm waters. Depending on their maximum sustained one-minute wind speed, they can be named and categorized as a tropical depression (low wind speed, less than 38 miles per hour), a tropical storm (moderate wind speed, between 39-73 miles per hour) or a hurricane (severe wind speed, greater than 74 miles per hour) (NPS, 2019). The term "hurricane" is used for the most powerful tropical cyclones that develop in the Atlantic Ocean and the Eastern Pacific Ocean, while tropical cyclones that develop in the Western Pacific Ocean are called "typhoons." For the remainder of the report, we will use hurricanes when referring to tropical cyclones as we focus our discussion on mangroves in the Gulf of Mexico and Caribbean, where tropical cyclones are referred to as hurricanes.

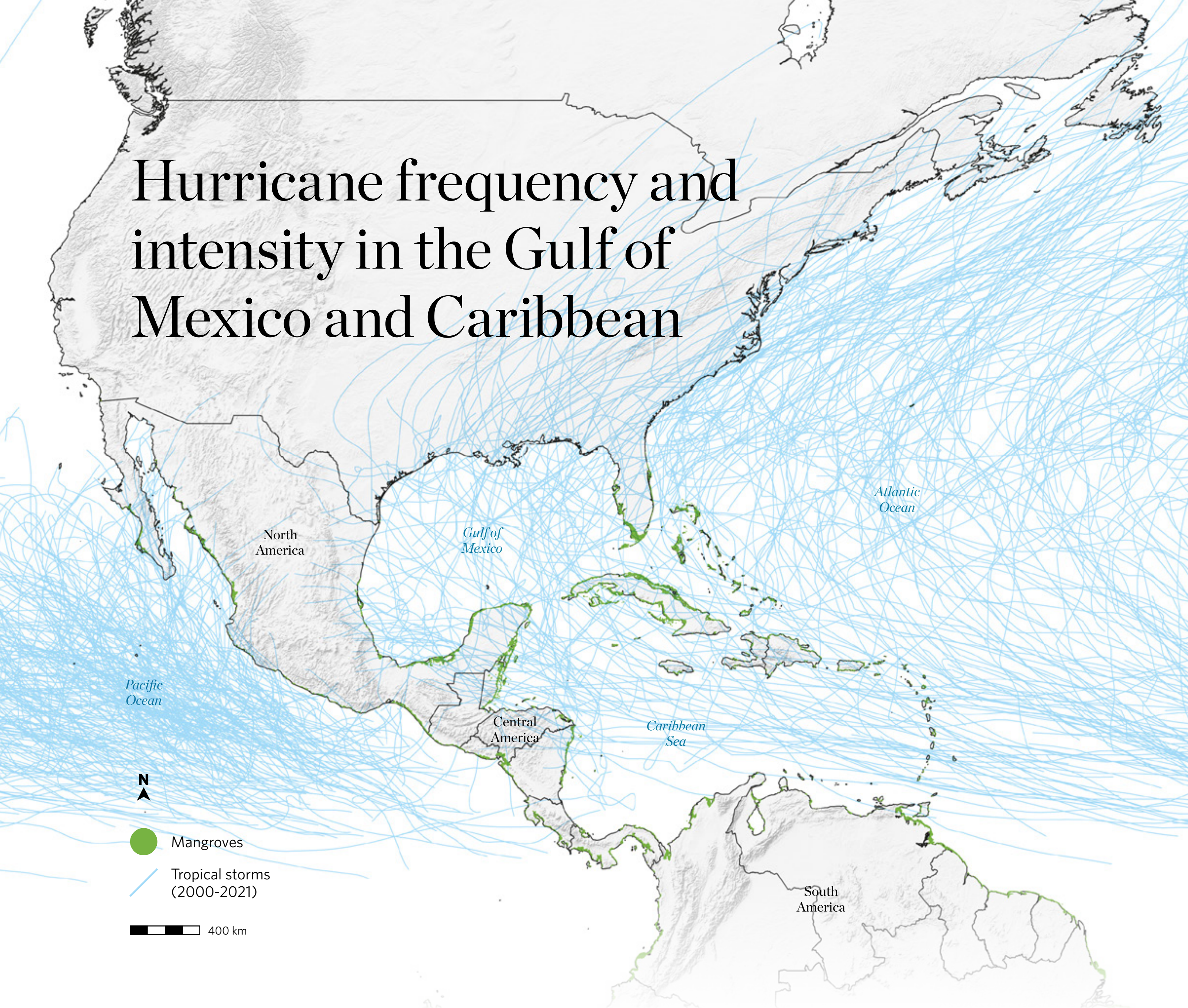
The Saffir-Simpson scale classifies hurricanes into five groups, with category five being the most severe hurricane category (NPS, 2019) (Figure 3). Hurricanes categorized as three and above are termed major hurricanes.

Conditions that are favorable for hurricane formation typically include a surface water temperature greater than 26°C, atmospheric humidity greater than 85%, and intense wind circulation due to the thermal difference between the ocean and the atmosphere (Yáñez-Arancibia *et. al.*, 2014). In the Atlantic and Caribbean, the hurricane season is from June to November, while in the Pacific it begins in May and ends in November.

Figure 3. Classification of hurricanes on the Saffir-Simpson scale (NPS, 2019).

Adapted from Lucia Guerra Cano.

Hurricane frequency and intensity in the Gulf of Mexico and Caribbean

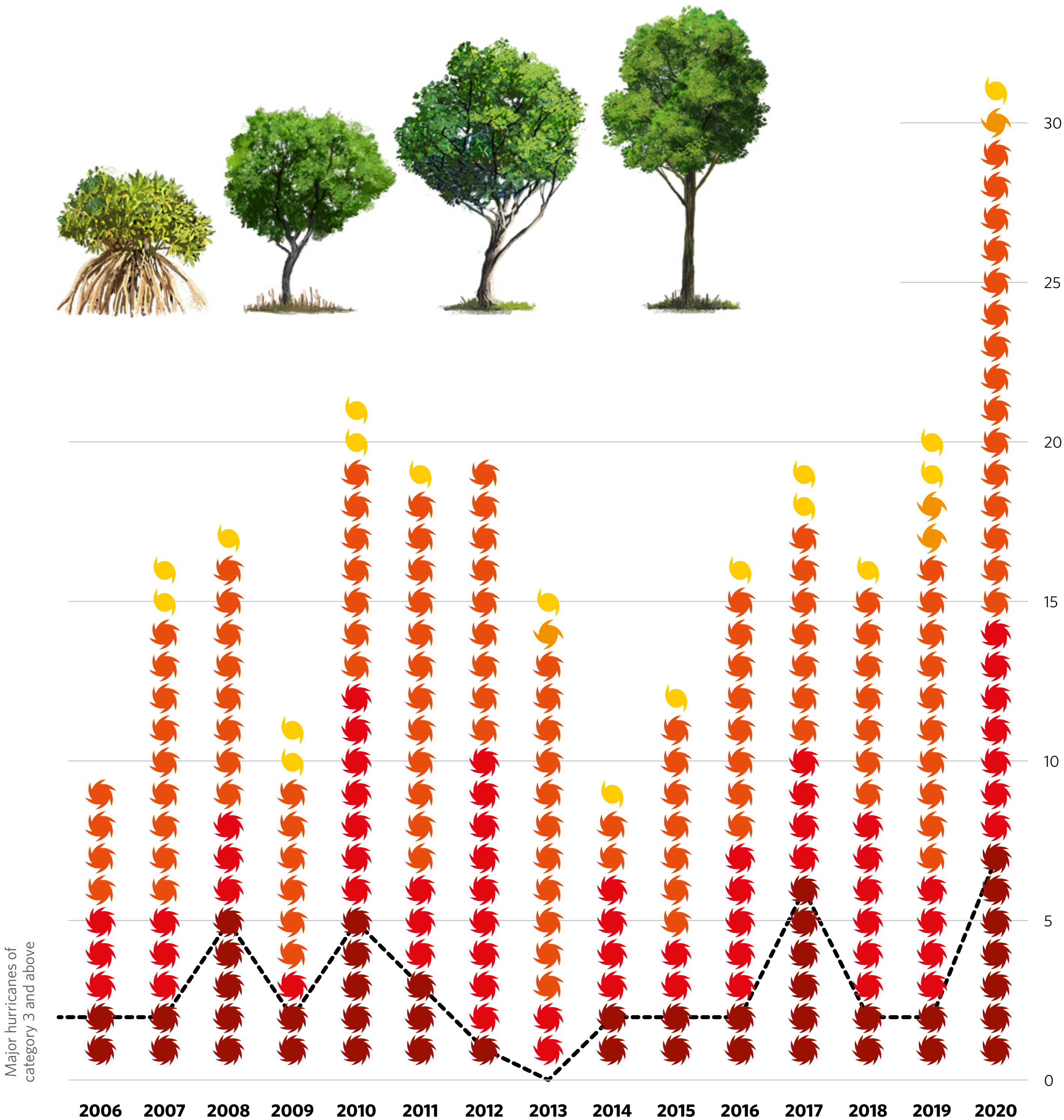


In the last 15 years, 250 hurricanes, tropical depressions, and tropical and subtropical storms have impacted the Gulf of Mexico and Caribbean (Figure 4). Up to 2019, the average number of named storms per season was 15, including six hurricanes, of which three were major hurricanes (Taillie *et al.,* 2020). The 2020 season was extremely intense with 31 storms, far above the average and surpassing all recorded seasons (Figure 5).

Over time, hurricane seasons have followed a polynomial tendency, where a considerable decrease in the number of storm events occurs every four to six years. However, since 2016, the number of major hurricanes has increased, in part due to an increase in sea surface and subsurface temperatures and a decrease in atmospheric circulation during the summer in the tropics (Taillie *et al.,* 2020). This increase in major hurricanes, together with other effects of climate change such as sea level rise, could cause even more severe damage to mangroves due to higher rates of coastal erosion, more severe flooding, and stronger storm surges with more extensive inland impact (Woodruff *et al*., 2013).

Figure 4: Track of hurricanes, tropical depressions, and tropical and subtropical storms in Gulf of Mexico and Caribbean (2000-2021)

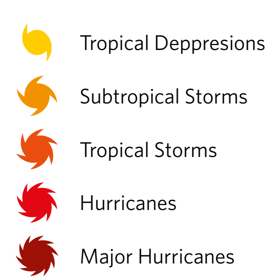
Source: NOAA's International Best Track Archive for Climate Stewardship (IBTrACS) data, accessed on January, 2022. Made with Natural Earth.



The number of tropical storms that have affected mangroves in the Gulf of Mexico and Caribbean from 2009 to 2017 was 116, of which 46 were classified as hurricanes (Taillie *et al*., 2020). In 2017 alone, over one million hectares of mangroves were affected by tropical storms or hurricanes, the largest mangrove area to be affected by storms in the last four decades (Taillie *et al*., 2020).

Figure 5: Number and intensity of tropical storm events per season in the Gulf of Mexico and Caribbean.

Source: SMN, 2021.



Influence of climate change in tropical storms

As climate change intensifies, conditions in the Atlantic Ocean become more favorable for the formation of hurricanes. Some authors predict large changes in tropical storm dynamics as a result of climate change, including an increase in the frequency of severe tropical storms; an increase in rainfall from the hurricane; and an increase in the number of tropical storms and hurricanes that reach northeastern United States, Canada, and even Europe (Knutson *et al.,* 2010, 2015; Christensen *et al*., 2013; Sobel *et al*., 2016; Kossin *et al.,* 2017; Patricola and Wehner, 2018).

These projections show that the negative effects of storms and hurricanes on mangrove ecosystems will also increase in the next several decades. Negative effects could include a reduction of organic matter and the replacement of mangroves by open water. However, on a regional scale, future changes to mangrove ecosystems are more complicated to predict (Krauss and Osland, 2020), since changing storm dynamics interact with other global change processes, such as sea level rise, erosion, and altered nutrient cycling (Osland *et al.,* 2018; Sippo *et al.,* 2018).

The island of Petit St. Vincent, Grenada. © Marjo Aho.

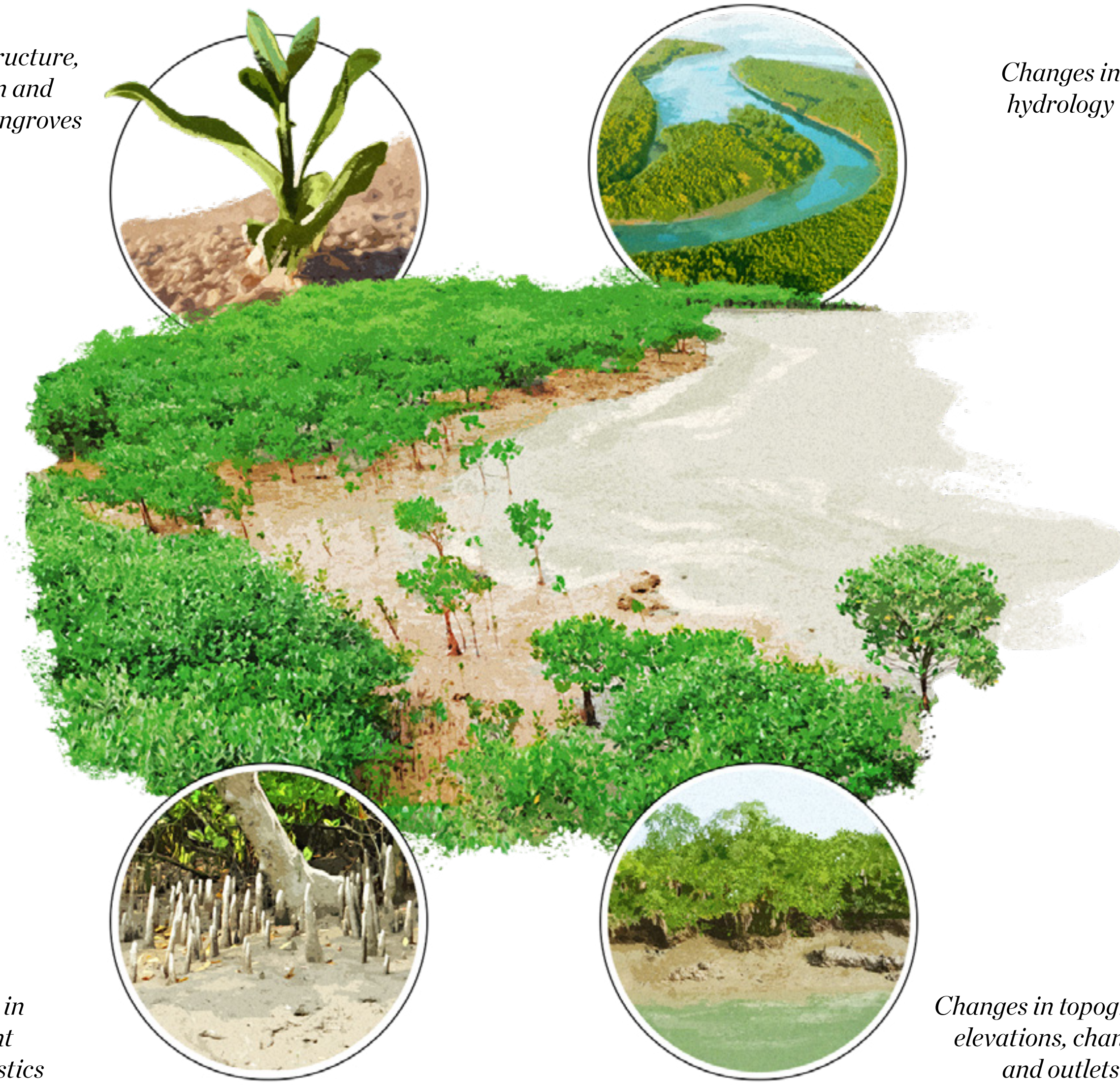
2

Damage caused by hurricanes to mangroves

Around the world, there are regions where mangrove forests are not affected by hurricanes because the climatic conditions do not favor storm formation; for example, hurricanes rarely affect mangroves in Africa, South America, Indonesia, and Papua New Guinea. However, there are other regions where mangroves are impacted by hurricanes, such as Australia, Mexico, Myanmar, the Philippines, Bangladesh, Cuba, and the United States. Small countries, such as The Bahamas, Guadalupe, Honduras, Belize and Haiti, which are home to large areas of mangrove forests, are located in some of the most active hurricane zones (Krauss and Osland, 2020).

Remnants of old pier and mangroves are seen in the erosion, Grenville Bay, Grenada. © Marjo Aho.

Types of damage



Mangrove forests are an important barrier to hurricanes along tropical and subtropical coasts. Hurricanes impact mangroves with strong winds, storm surge, sediment deposition, excessive flooding, and coastal erosion (Rodríguez-Ramírez *et al.*, 2008; Islebe *et al.*, 2009).

Hurricanes affect the structure and composition of the forest by uprooting and killing trees, breaking and knocking down stems and branches and defoliating the canopy, resulting in the modification of sediment dynamics, succession patterns, nutrient cycles, and a deterioration of forest structure and functions, and a decrease in biodiversity (Baldwin *et al.*, 2001; Herbert *et al.*, 1999). The impact of hurricanes can be classified by damages to the structure and composition of the forest, changes to the topography (elevation, channels, and outlets) of the area, changes to the hydrology, and changes to the characteristics of sediments (Figure 6).

Changes in structure, composition and biomass of mangroves

- Defoliation
- Loss of biomass (branches and trunks)
- Loss of mature trees by uprooting and death
- Reduction of the forest complexity
- Decrease in distribution and abundance of species
- Change in species dominance
- Change in frequency distribution of mature and juvenile trees
- Opening of clearings in the forest

Changes in topography: elevations, channels and outlets

- Trees, branches and sediments obstruct channels and outlets
- Influx of sediments raises the ground level of lagoons, channels and flooded areas
- Storm surge opens storm outlets in dunes and barrier islands
- Storm surge erodes and/or accretes the coastline

Changes in hydrology

- Disruption of water flow due to fallen trees or branches and/or sediment erosion and accumulation
- Increase in flood level
- Change in salt/freshwater balance
- Change in the hydroperiod

Changes in sediment characteristics

- Sediment salinization
- Suspended particles in the water column
- Changes in texture and composition of organic matter

Figure 6. Hurricane damage to mangrove forests.

Adapted from Lucia Guerra Cano.

Changes in structure, composition and biomass of mangroves

Damages to structure, composition and biomass of mangroves are the most evident impact of hurricanes. The damages consist of:

Defoliation. Strong gusts of wind during hurricanes cause leaves to detach (i.e., defoliation).

Branch breakage. Strong winds break or partially detach the branches of trees. Mature trees are affected the most as they have less flexibility than younger trees.

Trunk breakage. The severity of the disturbance is a function of the age of the community and size of the trees. Older trees grow tall, strong, solid and lack the flexibility to withstand wind forces. Individuals with trunk diameters more than 20 to 30 centimeters are susceptible to breakage during wind gusts (Islebe *et al.,* 2009). Younger and smaller individuals or those with smaller crowns are more flexible and resilient.

Root detachment. Wind gusts caused by major hurricanes can cause individual trees to be uprooted partially or completely and die. The survival of partially uprooted trees will depend on the conditions of the sediments and hydrological regimen post-storm.

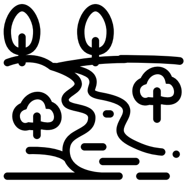
Reduction of complexity. The complexity of a forest refers to the structural and floristic characteristics and the degree of development of the system. The impact to any of these characteristics will cause a decrease in the complexity of the forest. Variables used to evaluate changes in complexity are the "value of importance" index (which measures the dominance of species), abundance, and the distribution of different trunk sizes and average tree height. These same characteristics should be monitored over time to determine the trajectory of recovery and the resilience of the system.

Decrease in distribution and abundance. The impact of a hurricane can rapidly transform the distribution and abundance of trees, generating conditions different from those prior to the storm. The abundance can decrease due to the death of individual mangrove trees. Trees may die immediately because of total detachment from the substrate or may die several months later due to defoliation, partial uprooting, and changes in environmental conditions that exceed the tolerance of each species. Conditions that are likely to be altered are flooding period, salinity, nutrient availability and sediment deposition (which interferes with the exchange of gases between the root and the sediment) (Lewis *et al.*, 2016). Tree distribution can be affected when changes in the environmental conditions affect mangrove species differently, favoring some species to the detriment of others.

Change in species dominance. Severe damage to dominant species in the mangrove forest facilitates the establishment of new species or growth of species whose dominance was lower. This replacement is caused by structural damage (uprooting or death of individuals) and the change in environmental conditions that may favor the less dominant species.

Change in the distribution and frequency of mature/juvenile trees. Mature trees with larger diameters are more susceptible to damage, so after a hurricane, juveniles may dominate the forest and mature individuals may be less frequent.

Opening of clearings. A clearing is an open area with no trees within a forest. Generally, they form naturally; however, this phenomenon is exacerbated by hurricanes when trees are felled or uprooted.

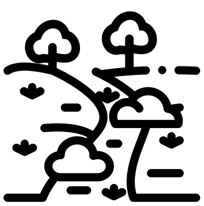


Changes in topography: elevations, channels and outlets

Hurricanes can transport large amounts of sediments into the coastal zone. Storm surge and currents can transport and relocate sediments along the coast, and intense rains can cause erosion inland and transport sediments downstream to interior lagoons and channels. In addition, strong hurricanes often breach barrier islands and open new storm outlets, allowing salty water to enter the system.

This sediment transport can produce significant changes in topography, such as raising the bottom of lagoons and mangrove areas, blocking natural channels where water used to flow, and even blocking outlets to the sea. Hurricanes can also produce huge amounts of debris, such as dead trees and broken branches that can block channels, disrupting the hydrological regime of the area.

Changes in topography could cause three effects: (i) higher elevation, which reduces water flow and the exchange of salts and nutrients, resulting in changes in the physical and chemical characteristics of sediments; (ii) lower topographic level, which raises flood levels to exceed the height of the seedlings, preventing their establishment and survival (Flores-Verdugo *et al.,* 2010); and (iii) opening of new outlets/inlets between the sea and wetlands, which can last for months or years, affecting the salinity of mangrove forests.



Changes in hydrology

As a consequence of topographic and physical changes, the hydrological regime on which mangroves depend can be impacted in the following ways:

Changes in the freshwater and marine water balance. New connections between sea and wetlands will increase the flow of salty water into the wetlands, modifying the pre-storm balance and changing the chemistry of the marshes and lagoons as well as the amount of water in the area.

Changes in the hydroperiod. This can occur due to the blockage of existing outlets or the opening of new outlets. The period and level of flooding can increase or decrease depending on whether outlets are blocked or opened.

Changes in water characteristics. Obstructed channels and new outlets/inlets generally alter and reduce hydrological flows, which can cause an increase in water salinity, an increase in sediment, an increase in water temperature, a reduction in oxygen concentrations, an increase in sulfide concentrations and/or variations in nutrient cycles. (Paling *et. al.,* 2008; Taillie *et. al.,* 2020). When inlets are opened by the storms, saltwater will flow inland and permeate marshes, lagoons, and other low-lying areas. Mangroves will survive or perish, depending on the tolerance of the species to these variations in water characteristics.

Increases in flood periods and levels. The increase in tide and precipitation during storms can cause areas near the coast to increase their flood periods and levels, which impact a mangrove's natural hydroperiod. The consequences of these changes can range from the "drowning" of seedlings or shrubby adults to increases in sulfide concentrations and negative oxidation-reduction levels (>-350 millivolts).

Mangroves along the coast of Warderick Wells Cay in the Bahamas Exuma Cays Land & Sea Park. © Mark Godfrey/TNC.

Changes in sediment characteristics

Sediment salinization. In areas where the water flow is interrupted, the concentration of salts can permeate the sediment. Inlets opened by the storm can allow greater intrusion of seawater, thus modifying the physicochemical conditions of the sediments. This can result in accelerated degradation of vegetation, affecting the forest structure and loss of ecosystem functions.

Burial of propagules. Accretion caused by storm surge can increase the elevation of the soil and bury propagules.

Hypoxia. Sediment deposition can change water flows, which subsequently may cause hypoxia (Cahoon *et al.*, 2002; Smith *et al.*, 2009). Tidal sediment deposition can limit the exchange of gases between soil and roots, also causing hypoxia.

Changes in texture and organic matter composition. The deposition of new sediments can change the composition and type of sediments. Heavy rains and increases in tide level can cause the deposition of sediments and organic matter in mangroves. In addition, winds and waves can loosen underground biomass, resulting in the reduction of soil consistency, favoring its sinking and causing changes in the topography and hydroperiod (Mazda *et al.*, 2002; Teutli-Hernández and Herrera-Silveira, 2016).

Severity of damage caused by hurricanes

MINIMUM

1. Slight defoliation
2. Breakage of small branches
3. Suspended particles in water column

MODERATE

1. Small and medium branch breakage
2. Moderate flooding (up to 2.5 meters)
3. Moderate channel sedimentation

EXTENSIVE

1. Breakage of large branches
2. Large volumes of fallen woody material
3. Extensive flooding (2.7 to 3.6 meters)
4. Hydrological flow disruption
5. Sediment salinization

EXTREME

1. Large trees downed/uprooted
2. Change in structure and composition (height and size)
3. Extreme flooding (3.9 to 5.5 meters)
4. Sea water intrusion
5. Opening of inlets through barrier islands or dune systems

CATASTROPHIC

1. No presence of seedlings or juveniles
2. Large trees downed/uprooted
3. Decrease in density and complexity
4. Catastrophic and prolonged flooding (higher than 5.5 meters)
5. Sediment salinization
6. Opening of inlets through barrier islands and dune systems

The severity of damage caused by hurricanes to mangroves depends on the condition of the mangroves and on the characteristics of the hurricane (intensity, wind speed, storm surge, size). Krauss and Osland (2020) propose a description of damages by hurricane intensity (Figure 7).

Figure 7. Extent of damage to mangroves based on hurricane intensity, using the Saffir-Simpson scale. Modified from Krauss and Osland, 2020.

3

Extent, location and severity of the damage

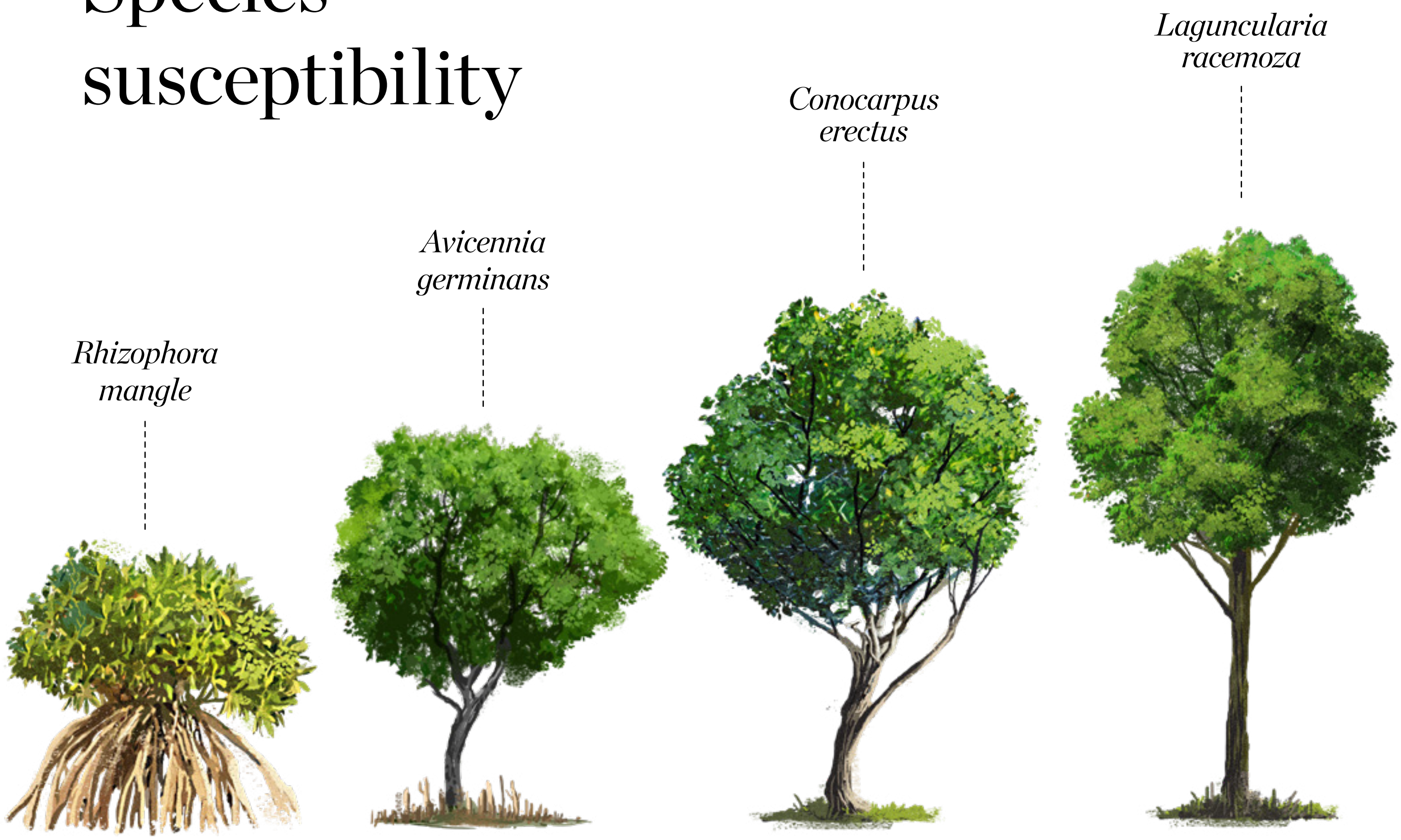
The extent and severity of mangrove forest damage that results from a hurricane is not homogeneous and varies depending on several factors. During the 2009 to 2017 hurricane seasons, Taillie *et al.* (2020) estimate mangrove damage to range from 86,439 to 133,662 hectares across the Gulf of Mexico, Caribbean, Central America, and South America. Other studies have found that the biomass of dead mangroves following a hurricane can reach 150 tons per hectare (Sánchez and Islebe, 1999).

When a hurricane makes landfall, it transfers its energy to the coastal system, where the fringing mangroves along the coastline receive the most violent impact (Carrillo *et al*., 2008). The proportion of damaged trees is higher in areas where there is a connection to open water.

Below, we describe well-documented factors that have contributed to the extent and severity of mangrove damage in the Gulf of Mexico and Caribbean.

Vegetation and mangrove crowd the shoreline of the Sian Ka'an Biosphere Reserve in the Pez Maya area of eastern Yucatan Peninsula in Mexico. © Edward Porter/TNC

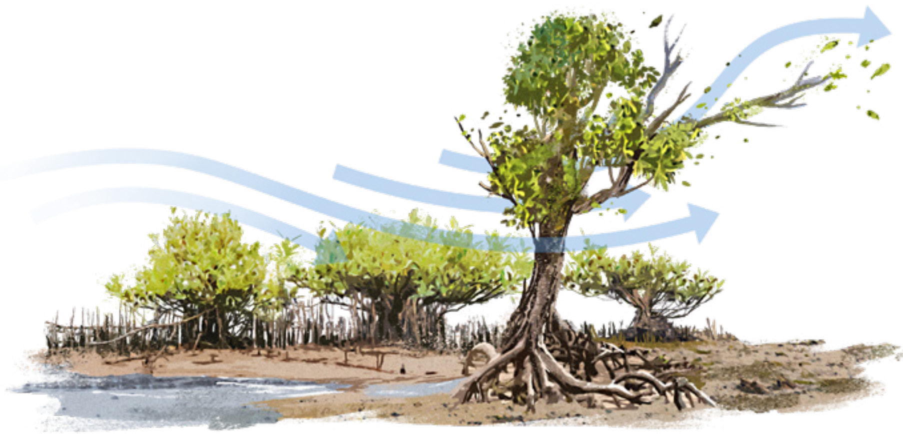
Species susceptibility



The susceptibility of different mangrove species to strong winds has been widely discussed by several authors. Kovacs *et al.* (2001) found that *Rhizophora mangle* is more resistant to hurricane winds than *Avicennia germinans*; however, Smith *et al.* (1994), Imbert *et al.* (1996) and Ross *et al.* (2006) had the opposite conclusion. And finally, Sherman *et al.* (2001), Milbrandt *et al.* (2006) and Smith *et al.* (2009) could not find differences in wind susceptibility between the two species. Several authors have reported that *Rhizophora mangle* is more damaged than *Avicennia germinans* and *Conocarpus erectus* when a low category hurricane occurs (Imbert *et al.*, 1996; Galeano *et al.,* 2007). Another species present in the Caribbean, *Laguncularia racemosa*, can be defoliated and uprooted by strong winds. Similar to *Avicinia germinans*, it can grow back if pore water salinity is below 40 ups. When *L. racemosa*'s trunk is fallen but roots remain alive, it will grow back and spur branches that will grow vertically as new trunks, as witnessed by Herrera's field experience. However, when major hurricanes occur, there are no significant differences between species because the wind gusts and storm surge are so violent.

Krauss and Osland (2020) conducted an analysis in the Caribbean and suggest that the tolerance of each mangrove species to hurricanes is influenced by the conditions of each site, the ecological type of mangrove, and the wind, rain, waves, and sedimentation generated by the particular storm.

Forest structure: trunk size and tree height



Individuals whose trunks have a diameter greater than 20 centimeters suffer more damage than individuals with smaller diameters since the wider the trunk the less flexible they are to resist wind gusts

In mature mangrove forests, smaller trees can resist strong winds more effectively, as opposed to taller trees, which are more likely to suffer breakage (Islebe *et al.*, 2009; Roth, 1992). Imbert (2018) reported that in mixed forests, the tallest species, *R. mangle*, suffered more lethal damage (80% of basal area loss) compared to *A. germinans* (20% of basal area loss) (Figure 8); the latter suffered lethal damage only when impacted by winds above 77 miles per hour.

With *basin mangrove forests*, storm surge deposits sediments which raises soil elevation, potentially drowning the vegetation and/or altering the salinity of the system (Smith *et al.*, 2009; Imbert, 2018). It has been observed that basin mangroves are more affected by tropical storms than riverine, marginal and insular mangroves. However, basin mangrove forests present a faster natural recovery because their primary productivity is higher (Imbert and Portecop, 1986; Imbert and Rollet, 1989).

Figure 8. Impact of hurricane winds in mangrove forests, where the tallest trees are the most affected by the passage of a hurricane.

Adapted from Javier Robles Toral.

Ecological type of mangrove

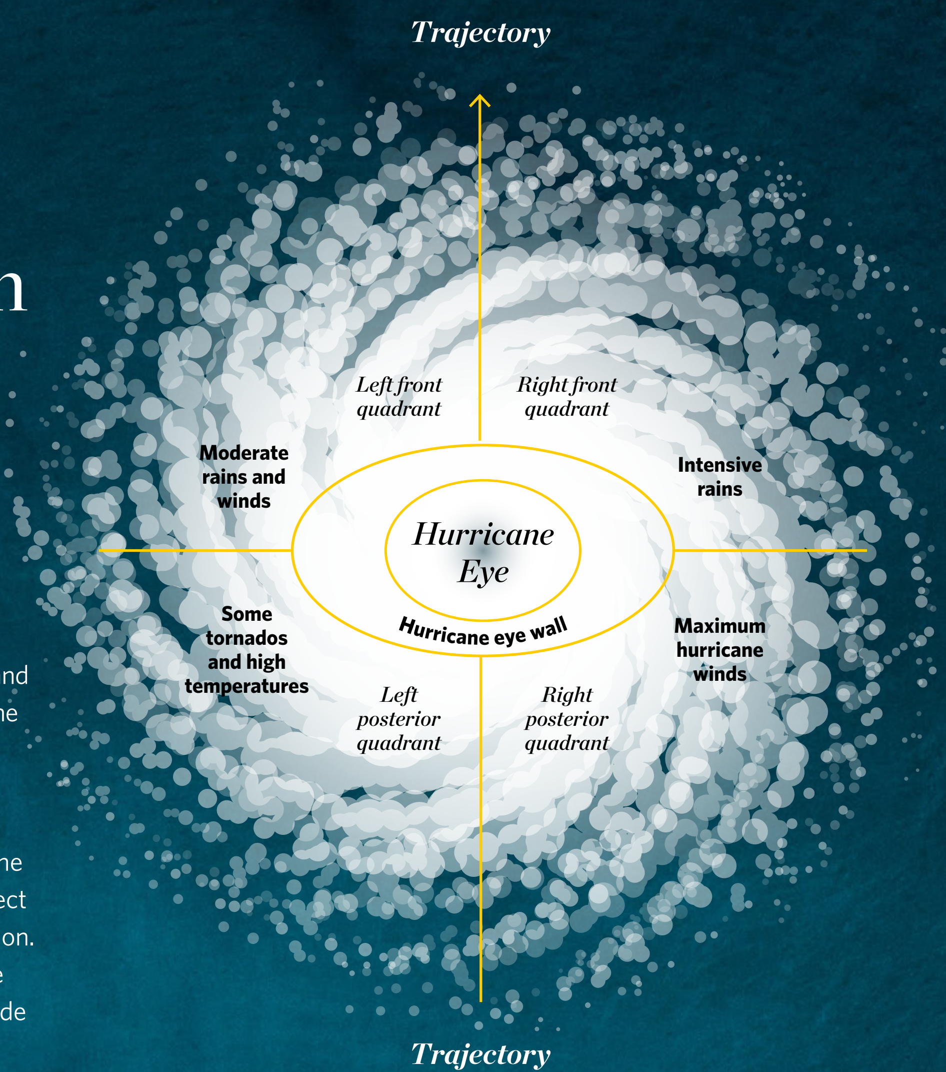
The ecological type of mangrove plays an important role in the severity of damage caused by storms and hurricanes. Hydrological and geomorphological characteristics of the site determine the mangroves ecological type, which in turn determines the structure and composition of the ecosystem (Lugo and Snedaker, 1974).

Fringing mangroves are located parallel to the coastline and next to the sea and are the first to be impacted by hurricanes (Carrillo *et al.*, 2008). They suffer more damage than other mangrove types.

Mangrove fragmentation or degradation

Coastal development and aquaculture have fragmented coastal ecosystems, including mangroves. Fragmentation affects the structure of the vegetation and hydrological flows, making them more susceptible to damage caused by natural phenomena such as tsunamis and hurricanes. In the Caribbean, mangroves located near populated areas and within the usual path of storms and hurricanes are more prone to damage due to the weakening of their structure (MEA, 2005).

Location of mangroves in relation to hurricane path and distance to the sea



The vulnerability of mangroves to loss or damage from hurricanes is influenced by their location in relation to the path of the hurricane, their exposure to the open sea, and the distance from the center of the hurricane (Baldwin, Egnotovich, Ford and Platt, 2001; Platt, Doren and Armentano, 2000).

The position of mangroves in relation to the path of the hurricane has a significant effect on the intensity of damage to the vegetation. In the Northern Hemisphere, the pressure exerted by wind and waves on the right side of a hurricane can be up to 25% greater than on the left side (Stanturf *et al*., 2007). Therefore, most hurricanes cause more damage on the right and front sides of the path of the eye. It has been observed that in the quadrants to the right of the hurricane path, the damage caused by Category 1 hurricanes are similar to those caused by Category 4 hurricanes (NASA, 2017). According to Novlan and Gray (1974), in the Caribbean, the most affected mangroves will be those located in the eye walls and in the front and rear right quadrants during the passage of the hurricane (Figure 9). The severity of damage decreases with increasing distance from the path of the eye of the hurricane (Dahal *et al*., 2014; Carrillo *et al*., 2008; Long *et al*., 2016).

The location of mangroves in relation to the open sea is also a determinant of damage. Mangroves located on the shoreline and adjacent to open water will suffer the greatest damage from waves and storm surge (Carrillo *et al.,* 2008; Long *et al.* 2016). Mangroves located on the landside of the system are generally composed of species with poorly developed root systems, such as *Conocarpus erectus* and *Laguncularia racemosa*. They are, therefore, more vulnerable to strong winds and severe damage has been observed (Long *et al.* 2016).

Figure 9. Hurricane zoning diagram. In the northern hemisphere, the right quadrants represent the hurricane's strongest rainfall and winds.

Adapted from Javier Robles Toral.

Frequency of hurricanes

Mangroves in the Gulf of Mexico and Caribbean adapted to be resistant and resilient to Category 1 and 2 hurricanes and can naturally recover in less than five years (Danielson *et al.,* 2017), but recovery may take longer (up to 20 years) when mangroves are impacted by major hurricanes of Category 3 and above (Imbert, 2018). An increase in the frequency and/or severity of hurricanes, as has been observed in recent years (Kossin, 2020), can disrupt mangroves' natural recovery and lead to an accumulation of damage (Taillie, 2020). Frequently impacted mangroves will have higher tree mortality, broken branches and defoliation, resulting in greater organic matter decomposition, increased soil formation and more compact soil (Snedaker, 1995; Lang'at *et al.*, 2014). These layered soil conditions, along with standing water, can hinder the mangroves' natural regeneration (Sherman *et al*., 2000; Cahoon *et al*., 2003).

Aerial photography of Punta Gorda, on Florida's Gulf of Mexico coast at the north end of Charlotte Harbor near the mouth of the Peace River. © Carlton Ward Jr.

4

Actions to restore or repair damages

As noted above, mangroves can naturally recover following a hurricane event. This recovery, however, can take several years leaving the mangroves vulnerable to additional storm damage while they are in the process of recovery. Active restoration and repair of mangrove forests following hurricane damage can quicken their recovery and enhance their resilience to future hurricanes. In this section, we describe common techniques for repairing and restoring mangroves. While we discuss mangrove restoration and repair in the context of addressing hurricane damage, many of the techniques described in this section can also be applied to restore mangroves that were not specifically damaged by a hurricane event. Indeed, there is growing interest and investments in ecological restoration of mangrove ecosystems (REM) (Mckee and Faulkner, 2000; Balke *et al.,* 2014; Dittmann *et al.,* 2019).

The type of mangrove restoration and repair needed will depend on the type and magnitude of the disturbance, as well as the environmental context in which it occurs. In all scenarios, it is recommended to apply a suite of actions and procedures to ensure successful mangrove recovery (Twilley and Rivera, 2005). There are four main steps in the design phase (Field, 1999, Teutli-Hernández *et al.,* 2020):

1. Characterize the physical and ecological conditions of the site.
2. Identify the factors regulating the dynamics of the site.
3. Identify the causes of degradation.
4. Locate the source of seeds and seedlings.

Mangrove roots grow from tidal sand flats along the coast of Warderick Wells Cay in the Exuma Cays Land and Sea Park, The Bahamas. © Jeff Yonover.

Mangrove Restoration Approaches

Hydrological rehabilitation

Removal of sediment, creation and maintenance of channels for water flow recovery.

Topographic rehabilitation

Modification of ground level according to sea level.

Reforestation

Planting mangrove seedlings. Recommended only when hydrological and topographic conditions are suitable for mangrove growth.

Figure 10. Common approaches to mangrove restoration.

The restoration actions commonly carried out can be grouped into three approaches, summarized in Figure 10.

Actions involved in hydrological rehabilitation

Figure 11. Actions involved in the hydrological rehabilitation of mangrove forest (Teutli-Hernández *et al.*, 2020).

Photos courtesy of Primary production laboratory-CINVESTAV.

The objectives of hydrological and topographic rehabilitation are to initiate or accelerate the recovery of environmental, hydrological, and physicochemical conditions that enable the establishment of vegetation and the return to an ecologically and functionally stable ecosystem (SER, 2002). However, natural regeneration has an important role to play. Mangroves recovered naturally in Guanaja, Honduras, 20 years after the impact of Hurricane Mitch in 1998 with similar results to reforestation projects in the same area (Fickert, 2020). It is recommended that all restoration projects involve local stakeholders in the restoration as community understanding of the purpose and value of the project enhances long-term project success (TNC, 2021). Conversely, poor management and limited consideration of ecological factors are the main reasons for failed restoration projects (Teutli-Hernández, 2017; Beck *et al.*, 2020).

Hydrological rehabilitation

The main objective of hydrological rehabilitation is to reestablish the hydrological flows, which are essential to maintain water salinity, temperature, turbidity and dissolved oxygen concentrations, as well as to the dispersion of propagules and seeds from healthy areas to the restoration site. Hydrological rehabilitation includes clearing of waterways and natural channels, excavation of new channels and maintenance of existing channels (Teutli-Hernández *et al.,* 2020) (Figure 11).

Hydrological rehabilitation begins by characterizing the site using aerial images and topographic assessments to identify areas where water flows have been altered, the routes of natural flows (freshwater or marine), possible trajectories for new channels, and channels that need maintenance (Teutli-Hernández *et al.,* 2020).

Dredging Channels

Dredging is the removal of sediments and debris deposited during the storm to recover the drainage capacity and optimize the circulation of water from one site to another. It is necessary to remove all organic and inorganic material that obstructs water circulation, maintaining the original characteristics of the channels (width, depth, extension, and direction, among others). It is essential to keep all the material removed

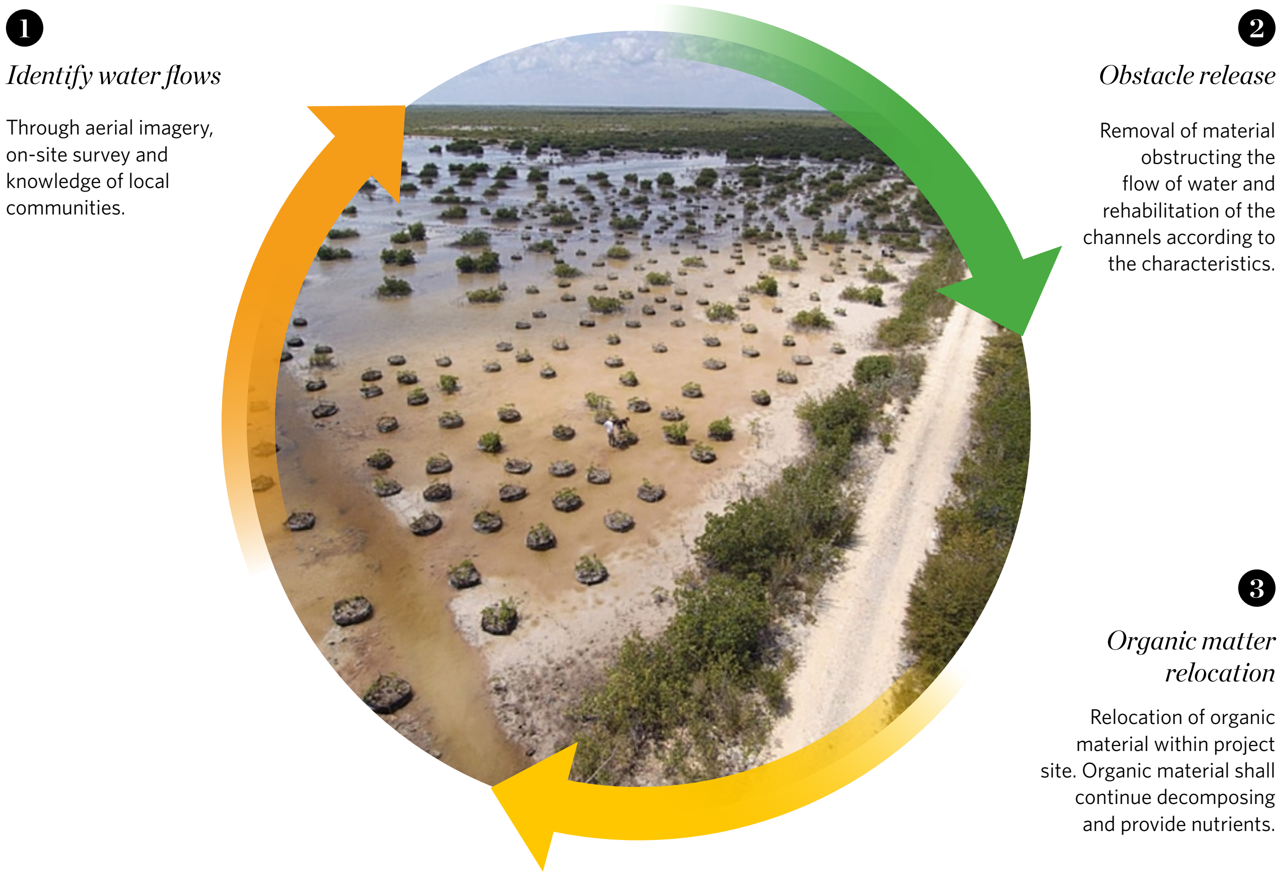


Figure 12. Process for the dredging of natural canals (Teutli-Hernández *et al.*, 2020).

Photo courtesy of Primary production laboratory-CINVESTAV.

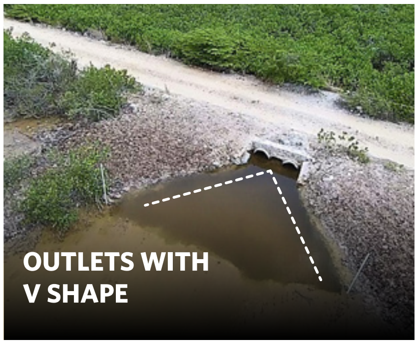
from the channels within the area to be restored, since this dredged material makes a considerable contribution to carbon storage (Teutli-Hernández *et al.*, 2020) (Figure 12). Place the dredged organic and inorganic material on the sides of the channels to minimize erosion, improve the flow of water, and improve the dispersion of propagules.

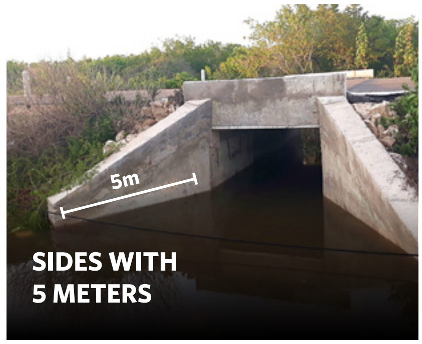
In some cases, dredging is sufficient to recover the hydrology of the site and the physical and chemical characteristics of the water and sediments, allowing the survival of individuals and facilitating the establishment of vegetation (Teutli-Hernández *et al.*, 2020).

Rehabilitation of water crossings

Road construction that disrupts the hydrological characteristics of coastal wetlands has been one of the main causes of mangrove degradation and decreased resilience to hurricanes, mainly due to the loss in hydrological connectivity and limited freshwater inputs (Lewis III, 2005; Wemple *et al.*, 2017; Teutli-Hernández and Herrera-Silveira, 2018). Properly designed culverts allow water flows to connect wetlands. However, most culverts do not meet the minimum requirements to allow an adequate exchange of water. Adapting these already existing culverts to allow an adequate exchange of water from well-preserved mangroves to disturbed mangroves may be sufficient.

Teutli-Hernández *et al.* (2020) suggest that culverts have an “approaching” V shape in both sides, widening immediately below the road towards the channels. The diverging lines of the “V” should have a length of at least five meters, a minimum depth of one meter, and connect with new or natural





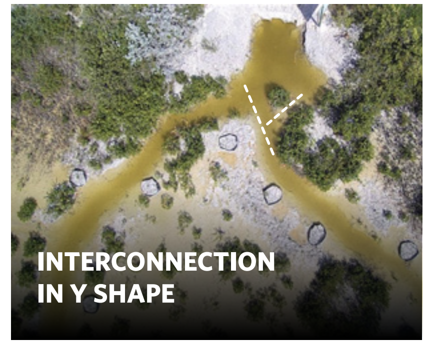


Figure 13. Structural characteristics in the rehabilitation of water crossings (Teutli-Hernández *et al.*, 2020).

Photos courtesy of Primary production laboratory-CINVESTAV.

channels, resembling a "Y." This adaptation in the structure of the culvert allows for better water circulation, as well as a greater range of water flow, even when there are low tides or increases in the hydroperiod, as in the case of hurricanes (Figure 13).

Opening new channels

The opening of new channels in degraded areas should be considered only when dredging natural channels is insufficient for the recovery of hydrological flow, or when natural channels were not identified. For example, the opening of a new channel may be appropriate when the topography of the terrain was raised by sediment deposition resulting in existing channels becoming silted in (Ramasubramanian and Selvam, 2011; Teutli-Hernández *et al.*, 2020).

For the excavation of these flow ways, it is recommended to use a system of "networks," which allow the water to be conveyed more efficiently from one site to another. The use of networks ensures the continuous flow of water without causing a new overflow (Teutli-Hernández *et al.*, 2020). Preferably, this system of networks would follow a "zig-zag" arrangement, with a system of main channels excavated at an angle of 45° to 90° with respect to the water source and a system of secondary channels, which should originate at an angle of 30° to 45° with respect to their main channel. (UNEP-Nairobi Convention, USAID and WIOMSA, 2020) (Figure 14). The depth and slope of the channels will depend on the tide level, preferential flows, and information obtained during site characterization. Again, it is recommended that the sediment and material removed be kept within the perimeter of the project (Teutli-Hernández *et al.*, 2020).

Figure 14. New channels enable hydrological rehabilitation (Teutli-Hernández *et al.*, 2020).

Photos courtesy of Primary production laboratory-CINVESTAV.

Figure 15. Actions involved in topographic rehabilitation of mangrove forests (Teutli-Hernández *et al.*, 2020).

Photos courtesy of Primary production laboratory- CINVESTAV.

Topographic rehabilitation

The hydrological characteristics of mangroves are closely related to the microtopography of the site and, in turn, both determine the establishment of species and the structure of the vegetation (Pérez-Ceballos *et al.,* 2017). As explained in section 2 changes in topography could cause two effects: (i) higher elevation, which reduces water flows and the exchange of salts and nutrients, resulting in changes in the physical and chemical characteristics of sediments and (ii) lower topographic level, which raises flood levels that will then more easily exceed the height of the seedlings, preventing their establishment and survival (Flores-Verdugo *et al.,* 2010).

The objective of topographic rehabilitation is to adapt the level of the land in relation to the mean sea level. In most cases, it is possible to use a nearby body of water and mangroves that are in good condition as references. Leveling can be done by removing sediments to reduce the height of the terrain or by the establishment of dispersal centers—raised platforms or terraces—to allow the establishment of seedlings (Teutli-Hernández *et al.,* 220) (Figure 15).

Sediment removal

The removal of sediment and organic and inorganic material aims to level the site by reducing the ground elevation (Teutli-Hernández *et al.,* 2020). When combined with the maintenance of water passages, the dredging of natural channels, and the creation of new channels, this action increases the resilience of the mangrove system and encourages repopulation by different species, favoring functional diversity, the process of secondary succession, and providing a greater probability of recovery after a natural or anthropogenic impact (Zedler, 2005).

It is recommended that the removed sediment be used to create dispersion centers or to fill sites with lower levels. These sites receiving the sediment should be identified by a topographic survey of the field that is then used to create a digital elevation model (DEM). The DEM can be used to create a network of preferential flows and to identify historic flow ways (Figure 16) (Teutler, 2005; Teutli-Hernández *et al.,* 2020).

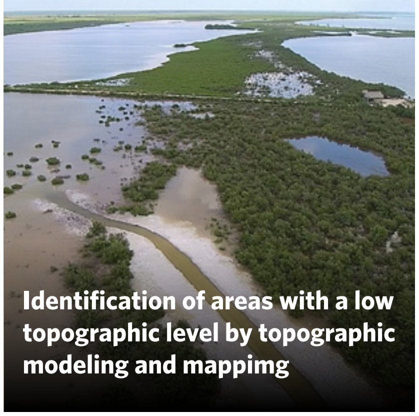


Figure 16. Sediment removal during topographic rehabilitation (Teutli-Hernández *et al.*, 2020).

Photos courtesy of Primary production laboratory-CINVESTAV.

Preparation of dispersion centers

The creation of dispersion centers consists of the construction of raised platforms to counteract periods of high flooding and tidal flows (Thivakaran, 2017). The shape of these platforms can be circular, square or irregular and should be built with sediment dredged at the site. These platforms facilitate the establishment of seeds and propagules with the goal of inducing natural regeneration or setting the stage for artificial reintroduction (Figure 17) (Teutli-Hernández *et al.*, 2020).

The use of dispersal centers for ecological restoration can produce better results than other actions since they promote greater survival at a lower economic cost (Febles-Patrón *et al.*, 2009; Thivakaran *et al.*, 2018). It is important to consider that the number, spacing and characteristics of the dispersal centers will be a function of the conditions of the area to be restored and the objectives and goals of the restoration (Teutli-Hernández *et al.*, 2020).

The heights of the dispersion centers should be varied to allow for the establishment of different species. The dispersion centers can be created, in part, through the reuse of material from other areas of the site, as long as it is permeable and not washed away (Figure 18) (Thivakaran *et al.*, 2018).

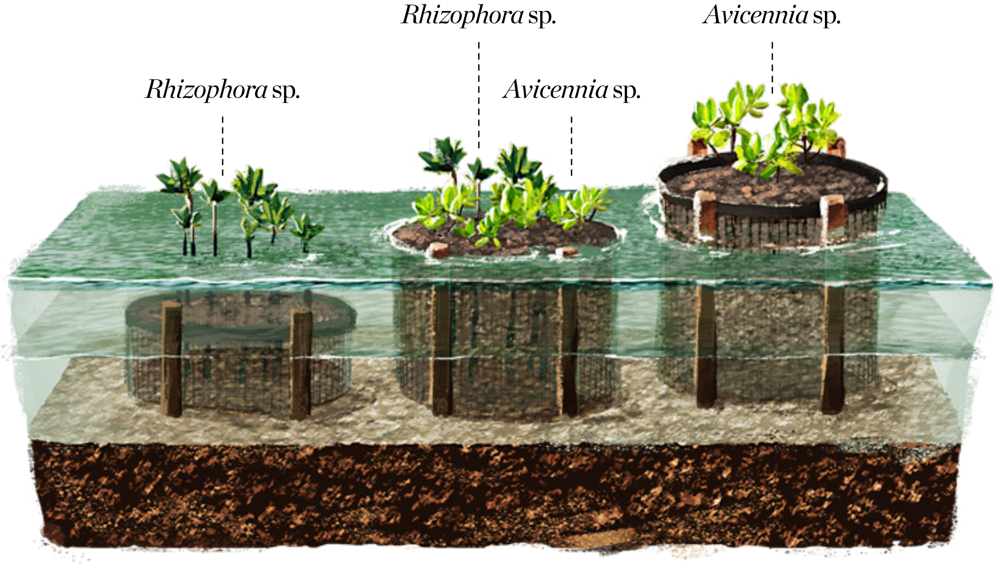


Figure 17. Illustration of dispersion centers with different topographic levels to generate heterogeneity in the landscape (Teutli-Hernández *et al.*, 2020).

Figure 18. Conditioning of dispersion centers (Teutli-Hernández *et al.*, 2020).

Photos courtesy of Primary production laboratory-CINVESTAV.

Reforestation

One of the most widely used techniques for mangrove forest restoration has been reforestation using propagules or nursery-grown seedlings. However, much of the information generated to date comes from trial and error focused on limited species. Guidelines for reforesting mangroves under different conditions are not clear, which has made it challenging to measure its effectiveness against other approaches (Elster, 2000; Teutli-Hernández, 2017; Fickert, 2020).

Reforestation should only be used when natural seed and propagule dispersal is insufficient (Teutli-Hernández *et al.*, 2020), as it may decrease the chances of survival. Also, reforestation efforts should only be carried out *after* assessing and ensuring the hydrological, sedimentological and topographical conditions at the site are adequate to sustain the ecosystem. If these conditions are not adequate, appropriate rehabilitation actions must be carried out prior to planting, as survival of the new seedlings and plantings requires a functioning ecosystem. These rehabilitation actions may be sufficient to allow the recovery of the ecosystem, in which case reforestation would not be necessary.

Nurseries are an expensive alternative to support reforestation since they involve raising seedlings year-round regardless of the natural cycle of the species. Additionally, it has been observed that seedlings from nurseries can suffer physiological stress, reducing their survival.

The seedlings and plantings should be maintained and monitored for at least five years due to relatively high mortality among newly planted nursery-raised seedlings. The first year is the most critical for survival as the roots are not yet firmly established and the seedlings can be dislodged by modest waves or wind and float away. In certain cases, newly planted seedlings may need protection from waves and currents until they grow strong roots and stems, especially when they are on the outer edges of the mangrove area or exposed to more open water. This can be accomplished through the construction of a temporary breakwater. A temporary breakwater should *only* be constructed after confirming the site characteristics are suitable for it and should be removed once the seedlings are established to avoid altering the hydrology and topography of the site.

5

Cost to restore mangroves

Black Mangrove seedlings, soon to be transplanted to a nursery area, Haiti. © Tim Calver.

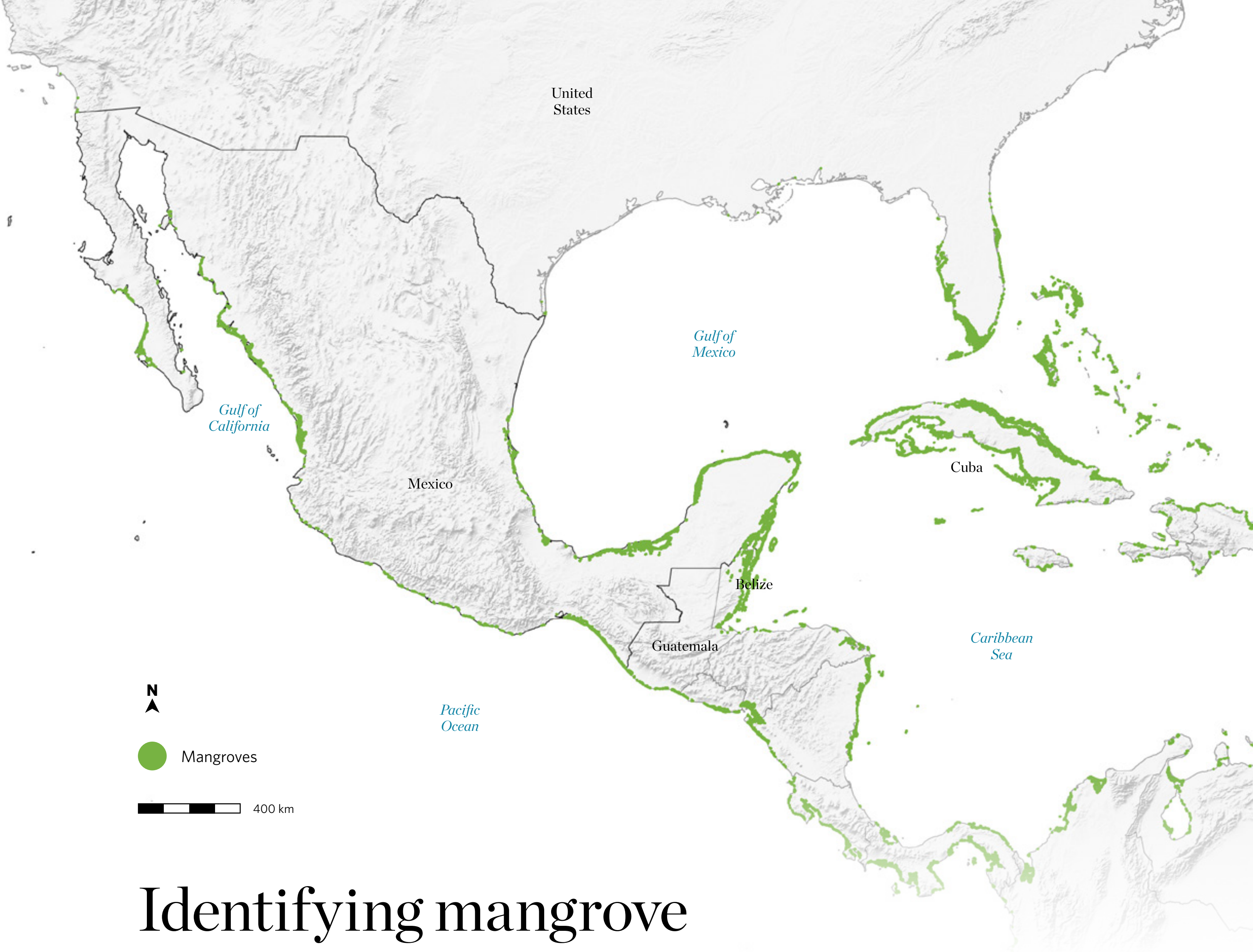
Understanding the costs typically associated with actions to restore mangroves is important for determining how best to allocate money to mangrove restoration projects. The cost of mangrove restoration varies widely across project types and geographies due to different factors such as:

- type of restoration action (e.g., dredging vs. reforestation);
- cost of materials and labor, which vary widely from country to country;
- distance and accessibility of the mangrove restoration site;
- land ownership of the site and local permit requirements;
- whether or not the restoration requires specialized machinery; and
- the scope of monitoring and maintenance implemented post-restoration, as in most cases, the cost of monitoring is not included in mangrove restoration costs (Narayan *et al.*, 2019).

We focused on identifying the range of costs of mangrove restoration projects in three regions: Mexico, Florida and The Bahamas. For each of these regions, we categorize restoration projects in as much detail as possible. In the case of Mexico, mangrove restoration projects are categorized by one or more of three broad approaches to mangrove restoration: (i) hydrological rehabilitation; (ii) topographic rehabilitation; and/or (iii) reforestation. In the case of Florida and The Bahamas, mangrove restoration projects are categorized by one or more of five specific actions taken to restore or repair mangroves: (i) breakwaters/revetments/riprap; (ii) channels/conveyance/culverts; (iii) excavation/fill; (iv) mangrove/wetland plantings; and/or (v) regrading/leveling.

In Florida and The Bahamas, the categorization of projects is based on restoration action because the cost of restoration is more strongly influenced by the action than the broader approach and objectives. There is also considerable overlap between project approaches since they are often interrelated and synergistic, and one or more of the identified actions could be used to achieve one or more of the project approaches. For example, reforestation by mangrove plantings could be combined with other methods such as regrading areas to the proper elevation (topographic rehabilitation) or creating channels through an area to improve tidal flows (hydrologic rehabilitation). In the case of restoration projects in Mexico, however, information on the restoration action was not available and, thus, we categorized projects by restoration approach. Before presenting a summary of mangrove restoration costs in each region, we briefly summarize the process used to identify relevant projects in each of the three regions below.

A wooden path winds through mangroves in Lucayan National Park on Grand Bahama Island, Bahamas. © Shane Gross.



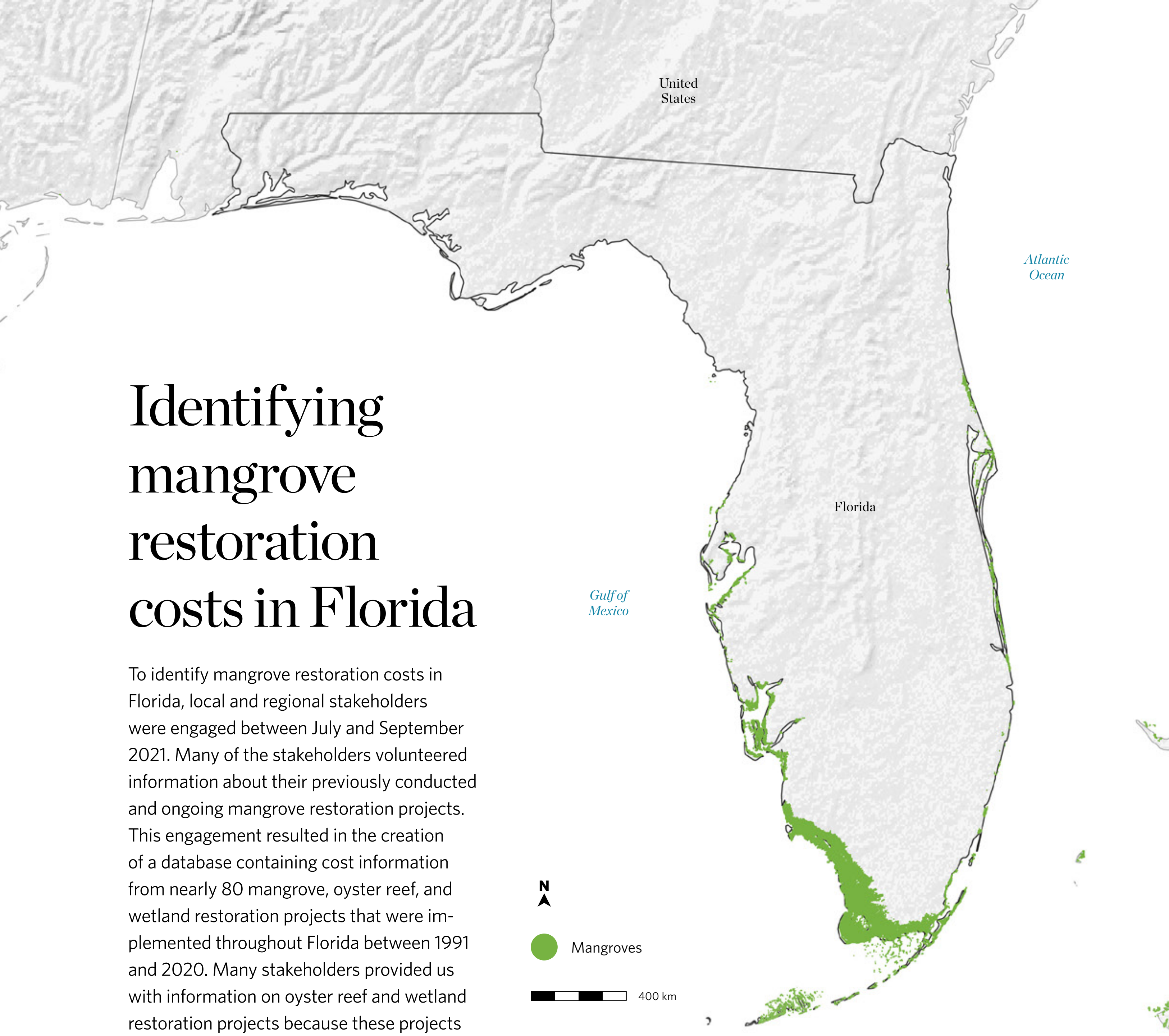
Identifying mangrove restoration costs in Mexico

Although several mangrove restoration efforts have been implemented in Mexico (both in the Gulf of Mexico and in the Mexican Caribbean), there is a lack of public information regarding the cost of restoration, as cost data from most mangrove restoration projects are contained in government and private sector technical reports, which are not shared publicly.

To estimate mangrove restoration costs, a systematic search of open access scientific articles and reports, which are available online at no cost, was conducted. All articles mentioning mangrove restoration costs in the Gulf of Mexico, the Mexican Caribbean, and/or the Caribbean Basin were retrieved. From this search, 26 sources of information on mangrove restoration project costs were compiled, including 16 sources from Mexico. All mangrove restoration project costs identified include funding for monitoring that occurred during the implementation of the intervention only. The data obtained were converted to U.S. dollars (USD) using the World Bank's exchange rate data and adjusted for inflation to 2021 USD based on data published by the Organization for Economic Cooperation and Development.

Source: Global Mangrove Partnership Dataset, World Atlas of Mangroves (Spalding, 2010). Made with Natural Earth.

Identifying mangrove restoration costs in Florida



Source: Global Mangrove Partnership Dataset, World Atlas of Mangroves (Spalding, 2010). Made with Natural Earth.

To identify mangrove restoration costs in Florida, local and regional stakeholders were engaged between July and September 2021. Many of the stakeholders volunteered information about their previously conducted and ongoing mangrove restoration projects. This engagement resulted in the creation of a database containing cost information from nearly 80 mangrove, oyster reef, and wetland restoration projects that were implemented throughout Florida between 1991 and 2020. Many stakeholders provided us with information on oyster reef and wetland restoration projects because these projects frequently include mangrove restoration or recruitment as a component of the project even if it is not the primary objective.

To provide more reliable mangrove restoration cost information, some data were filtered from the database. Restoration projects that focused primarily on oyster reefs or those without discernable details regarding the scope of work, project size or dates of completion were removed. Wetland restoration projects were deemed appropriate to include, however, since they often resulted in natural recruitment of mangroves. Several conservation partners indicated that natural recruitment of mangroves is their preferred method of reforestation since it can be significantly more successful than planting. The final database contains about 40 mangrove and wetland restoration projects. The project restoration costs were converted to a unit cost per hectare, which was adjusted to 2020 costs using the U.S. Bureau of Labor Statistics Consumer Price Index.

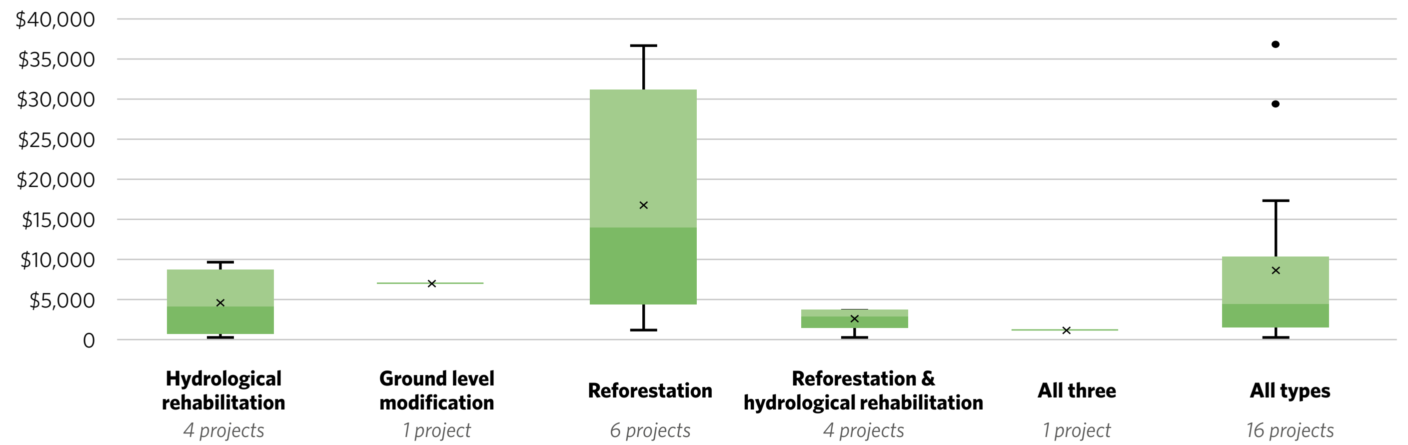
Source: Global Mangrove Partnership Dataset, World Atlas of Mangroves (Spalding, 2010). Made with Natural Earth.

Identifying mangrove restoration costs in The Bahamas

To identify mangrove restoration costs in The Bahamas, we conducted a desktop review of available information and we engaged key stakeholders leading mangrove restoration work in the country between September and October 2021. Through this process, a database was created containing 27 planned, ongoing, or completed projects from the past two decades. Project locations span the islands of Andros, Abaco, Grand Bahama, Long Island and New Providence.

The database was filtered to provide more reliable cost information. Restoration projects without details regarding the scope of work, estimated or actual cost, or size of the restored/affected area were removed. After this filtering, five projects remained. In several instances, a project employed more than one restoration action and, consequently, was categorized as using multiple actions. The project restoration costs were converted to a unit cost per hectare, which was adjusted to 2020 costs using the World Bank Consumer Price Index for The Bahamas.

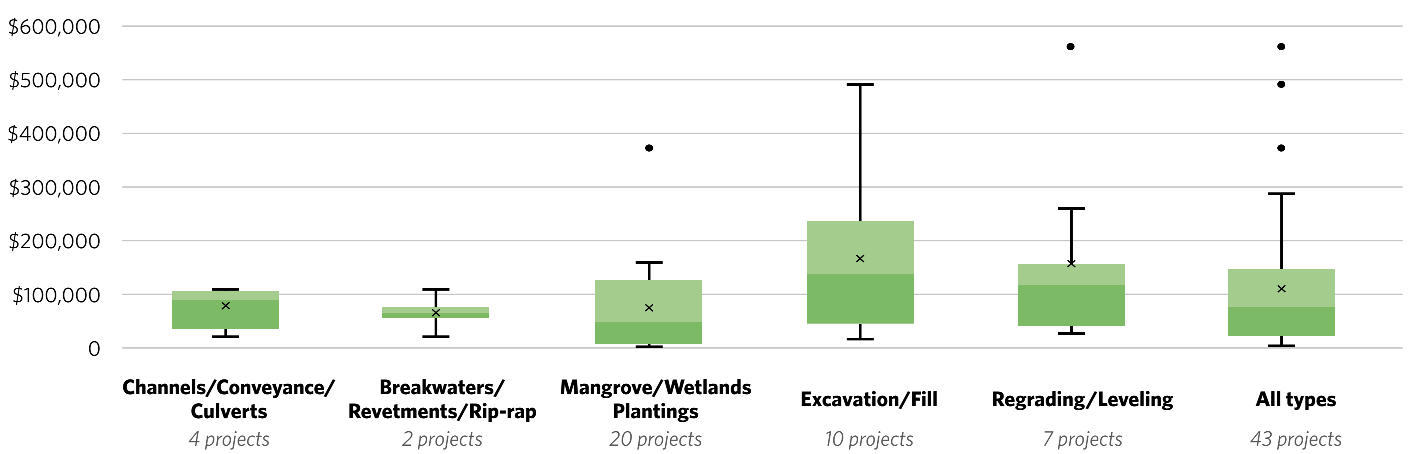
Mangrove restoration costs by approach or action



In Mexico, 16 mangrove restoration projects were identified, with nearly two-thirds (10) occurring in Veracruz alone. The documented project costs summarized by approach (topographical, hydrological or reforestation) (Figure 19) ranged from $170 per hectare to $37,000 per hectare.

Across all 16 projects, mean costs were $8,500 per hectare and median costs were $4,500. Mean and median restoration costs were highest for reforestation projects, where mean project costs were $16,700 per hectare and median project costs were $14,000 per hectare.

Figure 19. Mangrove restoration costs for 16 projects in Mexico, summarized by project approach and expressed in 2020 USD per hectare. Median costs denoted with a change of color and mean costs denoted with an X.



In Florida, 43 mangrove restoration projects were identified, with nearly two-thirds (27) occurring in Southwest Florida. The documented project costs summarized by restoration activity ranged from $500 per hectare to $562,000 per hectare, with a mean cost of $110,000 per hectare and a median cost of $77,000 per hectare (Figure20).

Nearly half (20) of the projects focused on mangrove/wetland plantings, which had the lowest restoration costs, with a mean cost of $54,000 per hectare and a median cost of $39,000 per hectare. In contrast, regrading/ leveling had the highest restoration costs, with a mean cost of $159,000 per hectare and a median cost of $117,000 per hectare.

Figure 20. Mangrove restoration costs by restoration activity for 43 projects in Florida, expressed in 2020 USD per hectare. Median costs denoted with a change of color and mean costs denoted with an X.

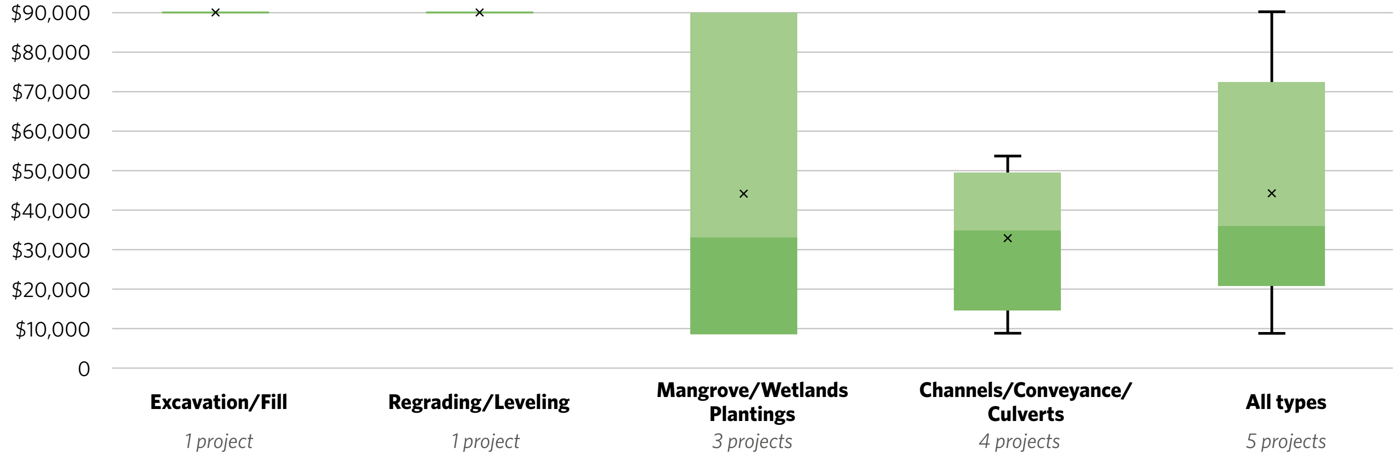


Figure 21. Mangrove restoration costs by restoration activity for 5 projects in The Bahamas, expressed in 2020 USD per hectare. Projects may have multiple restoration activities. Median costs denoted with a change of color and mean costs denoted with an X.

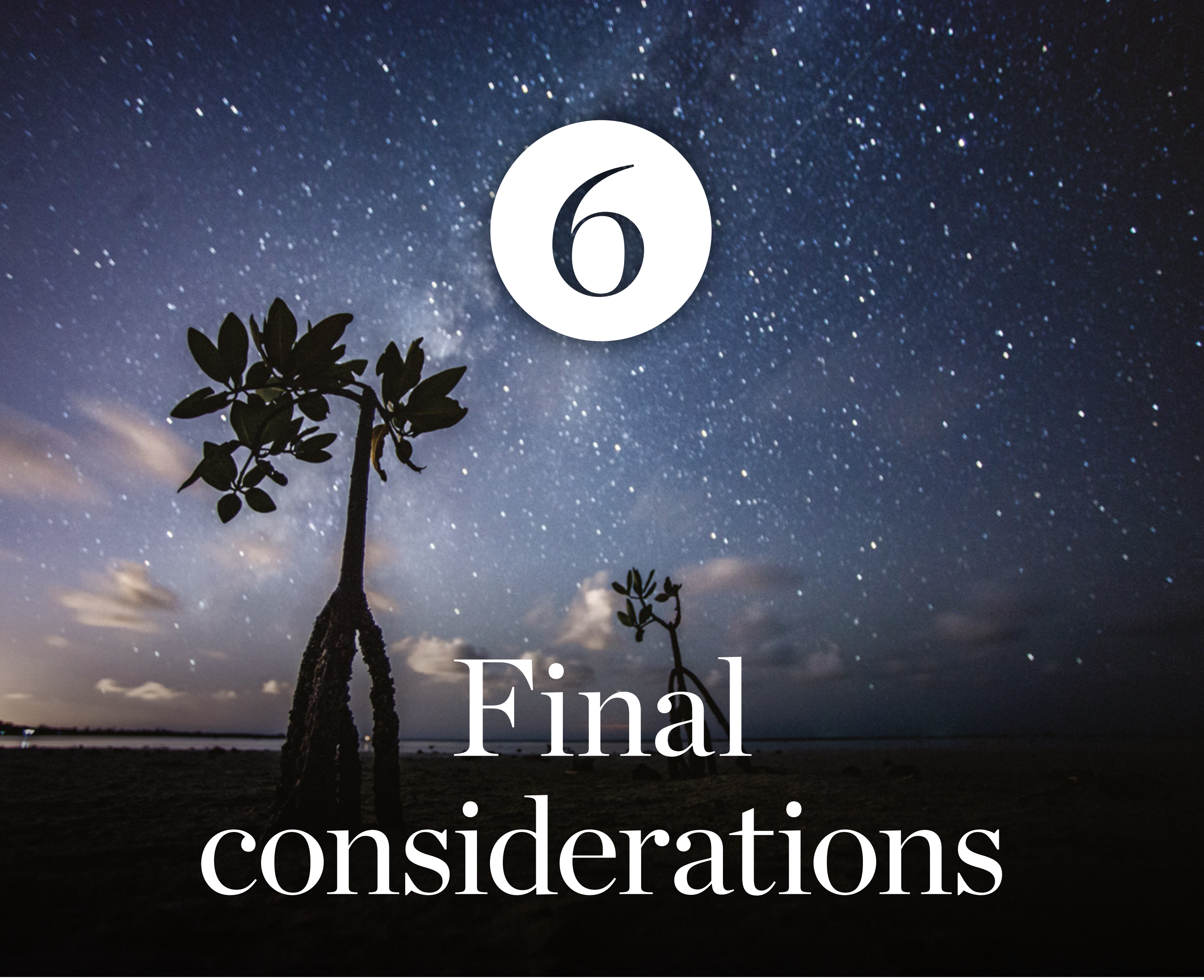
In The Bahamas, five mangrove restoration projects were identified, with documented costs ranging from approximately $8,000 per hectare to $90,000 per hectare, with a mean cost of $44,000 per hectare and a median cost of $36,000 per hectare (Figure 21). Four of the five projects involve restoration of hydrological flows in tidal creeks obstructed by roads and causeways without culverts, or by culverts that have been compromised and water flow is insufficient to maintain the ecosystem in its pre-construction state. These projects had lower restoration costs, with a mean of $33,000 per hectare and a median cost of $35,000 per hectare. In contrast, the restoration project costing $90,000 per hectare was the only one to include excavation and fill.

Country	Number of projects	Minimum cost per hectare (2020 USD)	Median cost per hectare (2020 USD)	Maximum cost per hectare (2020 USD)
Mexico	16	$170	$4,500	$37,000
Florida	43	$500	$77,000	$562,000
The Bahamas	5	$8,000	$36,000	$90,000

Table 1. Summary of mangrove restoration projects and costs by country.

Overall, the cost of restoration depends on the characteristics of the site, as well as on the type of action implemented. We find the median per hectare cost of mangrove restoration across all projects to be: $4,500 in Mexico (16 projects); $77,000 in Florida (43 projects); and $36,000 in The Bahamas (5 projects). These costs are in line with the ranges documented in previous studies (Table 1) (Narayan et al, 2019; Beck *et* al., 2020).

Several factors contribute to the wide range of project costs across the three regions. We found that mangrove restoration projects in Mexico tend to use far less machinery and heavy equipment, even when doing hydrological or topographic restoration. Second, labor costs vary widely among regions (e.g., labor costs in Mexico are one-tenth of labor costs in the United States). Further, in-kind costs provided by volunteers, partners and other donors are generally not accounted for in project cost totals.



6 Final considerations

Mangroves are a valuable ecosystem along tropical and subtropical coasts worldwide. In addition to the many other ecosystem services they provide, mangroves serve as a vital line of defense against tropical storms and hurricanes, reducing storm surge and dissipating wave energy during storm events, which can lead to significant reductions in inland flooding (Beck *et al.*, 2020). As a result, mangrove ecosystems can sustain severe damage, including tree loss and changes in the ecosystem's sediment conditions and hydrology, to name a few.

Researchers in Mexico have observed that mangroves in the Yucatan Peninsula are resilient to storm events as long as their condition is healthy prior to the event (Islebe *et al.,* 2009; Herrera-Silveira *et al.,* 2010). When a mangrove is healthy, the average period for natural recovery is 7-13 years. However, when mangroves are already degraded, the recovery time can exceed 20 years, and in the worst cases, mangroves may never recover without human intervention. In all cases, the length of time to recovery can be shortened if post-storm restoration actions are quickly

Isla Blanca, Isla Mujeres, Quintana Roo. © Carlos Gustavo Blanco Matus/TNC Photo Contest 2021.

implemented. In healthy mangroves, recovery times can be reduced by up to 50% with the implementation of post-storm restoration actions. These actions may be especially important to implement if the frequency of storm events increases and the recovery time between storm events decreases, as some researchers predict will occur.

Fortunately, implementing mitigation and restoration measures prior to storm events can reduce the cost of repairing damages to mangroves after a storm event. Mangrove ecosystem restoration has been widely carried out in the Gulf of Mexico and Caribbean since the 1970s. Drawing on experiences learned from those ecosystem restoration projects and the techniques cited in this report, we recommend that any restoration project include:

1. The identification of mangrove areas that have some degree of deterioration (spatial and field analysis);
2. the implementation of actions aimed at the recovery of these areas;
3. the continued monitoring of the restored area using drone or satellite images and field surveys.

As previously discussed, the cost to restore mangroves can vary widely both across geographies and restoration activities.

Across our three priority regions, we documented a median per hectare cost of mangrove restoration to be $4,500 in Mexico, $77,000 in Florida and $36,000 in The Bahamas. Across all 64 mangrove restoration projects we reviewed, per hectare costs ranged from $200 to $562,000.

In this report, we have reviewed the potential damages incurred by mangroves as a result of hurricanes and the potential actions that can be taken to restore damaged mangroves. It is our aim that practitioners and other relevant stakeholders can use this information to better understand the importance of restoring and repairing mangroves both before and after storm events. Understanding what restoration action is necessary is critical to ensuring the success of the restoration project. In addition, the cost of restoration can help individuals advocate for cost-effective restoration projects. Mangrove forests can serve as a vital first line of defense, but only if they are maintained, restored, and managed with science-based policies and practices.

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Appendix

Table A1: List of Mangrove Restoration Projects Included in Cost Analysis

Country	Restoration Approach / Activity	Year	Costs per Hectare (2020 USD)
Gulf of Mexico, México	Ground level modification	Not Available	$6,964
Gulf of Mexico, México	Hydrological rehabilitation	Not Available	$9,730
Gulf of Mexico, México	Hydrological rehabilitation	Not Available	$170
Gulf of Mexico, México	Hydrological rehabilitation	Not Available	$2,341
Gulf of Mexico, México	Hydrological rehabilitation	Not Available	$5,708
Gulf of Mexico, México	Reforestation	Not Available	$1,158
Gulf of Mexico, México	Reforestation	Not Available	$29,292
Gulf of Mexico, México	Reforestation	Not Available	$36,652
Gulf of Mexico, México	Reforestation	Not Available	$10,577
Gulf of Mexico, México	Reforestation	Not Available	$5,354
Gulf of Mexico, México	Reforestation	Not Available	$17,352
Gulf of Mexico, México	Reforestation and hydrological rehabilitation	Not Available	$3,687
Gulf of Mexico, México	Reforestation and hydrological rehabilitation	Not Available	$3,722
Gulf of Mexico, México	Reforestation and hydrological rehabilitation	Not Available	$1,203
Gulf of Mexico, México	Reforestation and hydrological rehabilitation	Not Available	$2,072
Gulf of Mexico, México	Reforestation, hydrological rehabilitation and ground level modification	Not Available	$1,243
Florida, USA	Channels/Conveyance/Culverts	2021	$98,800
Florida, USA	Channels/Conveyance/Culverts	2021	$111,150
Florida, USA	Channels/Conveyance/Culverts	2021	$83,980
Florida, USA	Channels/Conveyance/Culverts	2006	$17,095
Florida, USA	Breakwaters/Revetments/Riprap	2016	$53,159
Florida, USA	Breakwaters/Revetments/Riprap	2015	$76,869
Florida, USA	Mangrove/Wetland Plantings	1991	$132,812
Florida, USA	Mangrove/Wetland Plantings	1992	$8,825
Florida, USA	Mangrove/Wetland Plantings	1992	$158,856
Florida, USA	Mangrove/Wetland Plantings	1994	$112,983
Florida, USA	Mangrove/Wetland Plantings	1996	$159,749
Florida, USA	Mangrove/Wetland Plantings	1998	$54,653

Florida, USA	Mangrove/Wetland Plantings	1999	$75,012
Florida, USA	Mangrove/Wetland Plantings	2005	$141,509
Florida, USA	Mangrove/Wetland Plantings	2006	$373,099
Florida, USA	Mangrove/Wetland Plantings	2007	$37,768
Florida, USA	Mangrove/Wetland Plantings	2019	$1,256
Florida, USA	Mangrove/Wetland Plantings	2019	$66,112
Florida, USA	Mangrove/Wetland Plantings	2019	$15,701
Florida, USA	Mangrove/Wetland Plantings	2019	$1,960
Florida, USA	Mangrove/Wetland Plantings	2019	$5,583
Florida, USA	Mangrove/Wetland Plantings	2019	$628
Florida, USA	Mangrove/Wetland Plantings	2019	$104,677
Florida, USA	Mangrove/Wetland Plantings	2019	$502
Florida, USA	Mangrove/Wetland Plantings	2019	$44,074
Florida, USA	Mangrove/Wetland Plantings	2020	$12,350
Florida, USA	Excavation/Fill	2013	$288,824
Florida, USA	Excavation/Fill	2013	$93,806
Florida, USA	Excavation/Fill	2013	$191,315
Florida, USA	Excavation/Fill	2013	$40,732
Florida, USA	Excavation/Fill	2013	$125,897
Florida, USA	Excavation/Fill	2013	$220,938
Florida, USA	Excavation/Fill	2013	$492,481
Florida, USA	Excavation/Fill	2019	$46,058
Florida, USA	Excavation/Fill	2017	$14,967
Florida, USA	Excavation/Fill	2014	$148,927
Florida, USA	Regrading/Leveling	2017	$157,315
Florida, USA	Regrading/Leveling	2008	$38,467
Florida, USA	Regrading/Leveling	2010	$148,050
Florida, USA	Regrading/Leveling	2010	$561,795
Florida, USA	Regrading/Leveling	1997	$117,214
Florida, USA	Regrading/Leveling	2020	$64,220
Florida, USA	Regrading/Leveling	2012	$24,728
The Bahamas	Excavation/Fill, Regrading/Leveling, Mangrove/Wetland Plantings	2013	$90,073
The Bahamas	Channels/Conveyance/Culverts, Mangrove/Wetland Plantings	2016-2022	$8,486
The Bahamas	Channels/Conveyance/Culverts	2021	$53,846
The Bahamas	Channels/Conveyance/Culverts	2021	$35,955
The Bahamas	Channels/Conveyance/Culverts, Mangrove/Wetland Plantings	Not Available	$33,097

Hurricane Damages *to* Mangrove Forests

and Post-Storm Restoration Techniques and Costs

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