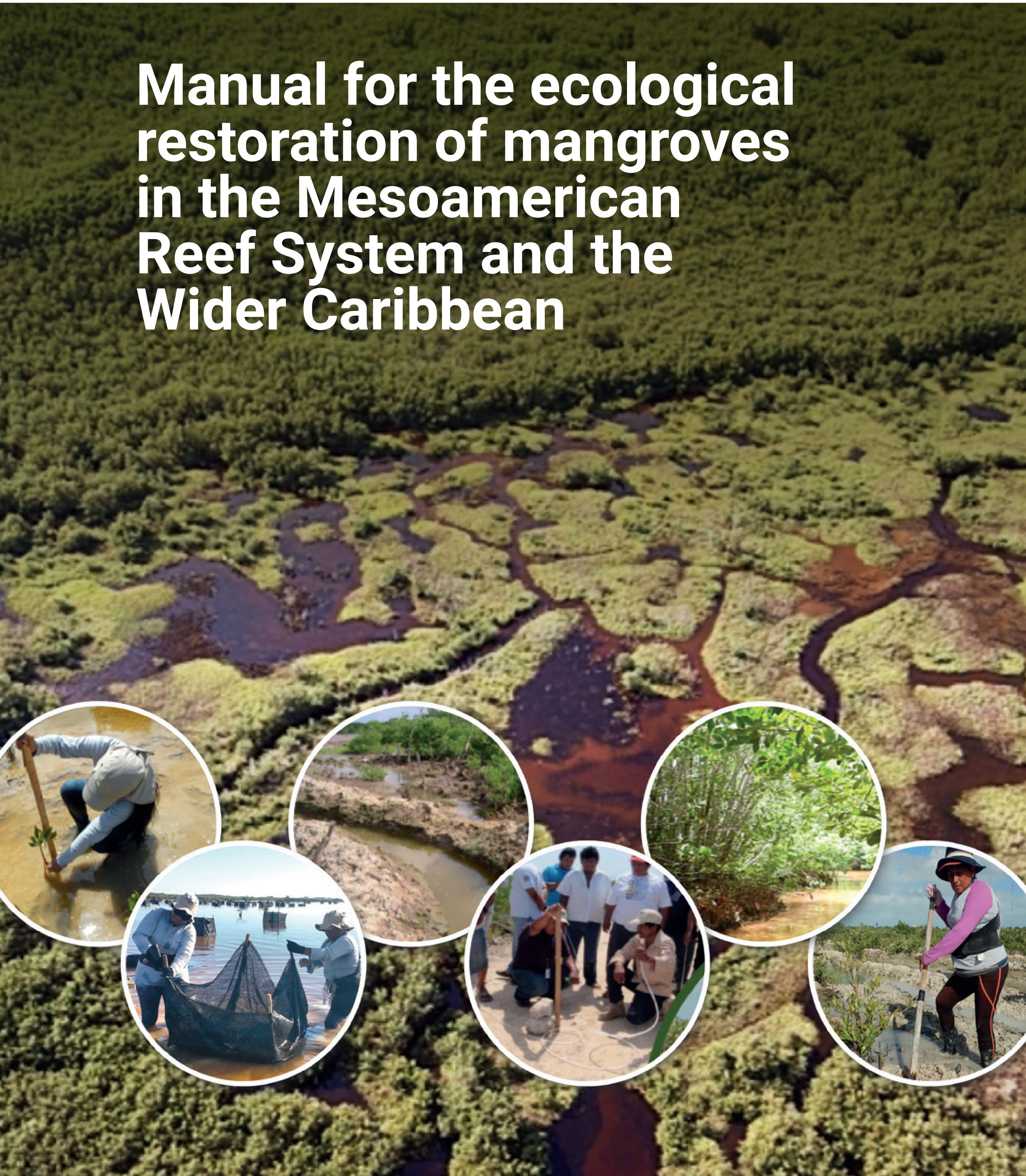
INTEGRATED RIDGE TO REEF MANAGEMENT OF THE MESOAMERICAN REEF ECOREGION PROJECT (MAR2R)

Manual for the ecological restoration of mangroves in the Mesoamerican Reef System and the Wider Caribbean



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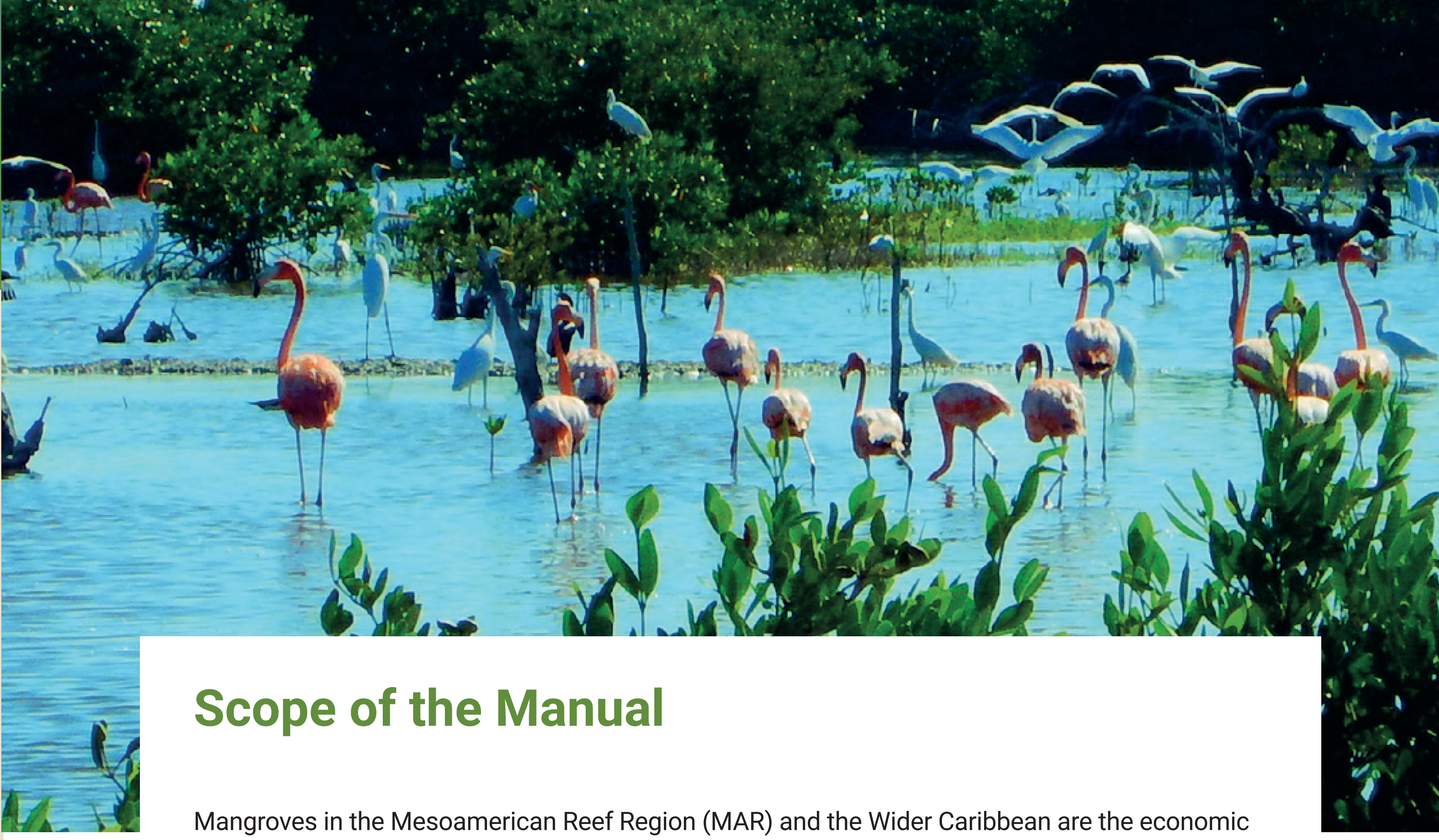


O.J. Pérez, Progreso, Yucatán, México

Scope of the Manual

Mangroves in the Mesoamerican Reef Region (MAR) and the Wider Caribbean are the economic foundation of over 134 million people living in the coastal regions. Mangroves provide protection against floods and buffer against storms and hurricanes, to which the region is highly vulnerable. Additionally, due to their close relationship with other ecosystems, such as coral reefs and seagrasses, mangroves and the ecosystem services they provide are the conservation pillars of coastal ecosystems.

Among these services, the storage potential of blue carbon is one of the most essential services in mitigating the effects of climate change, in addition to supporting important tourism and fisheries industries. However, every year the extent of mangroves continues to decline due to the impacts of climate change, change in land use, and the overexploitation of resources.

This manual contributes to strengthening local, national, and regional capacities for the ecological restoration of mangroves and the ecosystem services they provide in the MAR and the Wider Caribbean region. Within the framework of the Cartagena Convention and the United Nations Decade on Ecosystem Restoration 2021-2030, ecological restoration (ER) of mangroves is considered a Nature-based Solution (NbS) that allows addressing the effects of climate change. This favors biodiversity conservation and the economic well-being of the population, contributing to the United Nations Sustainable Development Goals.

Mangrove ecological restoration in the MAR and the Wider Caribbean is a priority in the Regional Environmental Framework Strategy (ERAM, for its initials in Spanish) of the Central American Commission for Environment and Development (CCAD, for its initials in Spanish), in the development of the Blue Economy Regional Protocol, led by the MAR2R/CCAD/WWF-GEF Project as well as in the Regional Strategy and Action Plan for the Valuation, Protection and/or Restoration of Key Marine Habitats in the Wider Caribbean 2021-2030 (RSAP), developed under the Specially Protected Areas and Wildlife (SPAW) subprogram of the Cartagena Convention.

Content

Acronyms and initials

CCAD	Central American Commission for Environment and Development
CICY	Scientific Research Center of Yucatan (Mexico)
CINVESTAV	Center for Research and Advanced Studies (Mexico)
CLME+	Caribbean and North Brazil Shelf Large Marine Ecosystems
CONABIO	National Commission for the Knowledge and Use of Biodiversity (Mexico)
CONAFOR	National Forest Commission (Mexico)
CONANP	National Commission for Natural Protected Areas (Mexico)
CSIC	High Council for Scientific Research (Spain)
DOE	Department of the Environment (Belize)
DUMAC	Ducks Unlimited de México, A.C.
ERAM	Regional Environmental Framework Strategy
FAO	Food and Agriculture Organization of the United Nations
FFCM	Flora, Fauna y Cultura de México, A.C.
GEF	Global Environment Facility
INECC	National Institute of Ecology and Climate Change (Mexico)
IPN	National Polytechnic Institute (Mexico)
JICA	Japan International Cooperation Agency
LME	Large Marine Ecosystem
MAR	Mesoamerican Reef
MARN	Ministry of Environment and Natural Resources (Guatemala)
MER	Mangrove Ecological Restoration
NbS	Nature-based Solutions
RSAP	Regional Strategy and Action Plan for the Valuation, Protection and/or Restoration of Key Marine Habitats in the Wider Caribbean
SEMARNAT	Secretariat of Environment and Natural Resources (Mexico)
SER	Society of Ecological Restoration
SPAW	Specially Protected Areas and Wildlife
UN	United Nations
UNAM	National Autonomous University of Mexico
UNEP-CEP	Caribbean Environment Programme of the United Nations Environment Programme
WWF	World Wildlife Fund

Objective

The objective of the manual is to guide and strengthen local and regional capacities of all those (individuals, groups, organizations) interested in recovering mangrove ecosystems in the Mesoamerican Reef Region (MAR) and the Wider Caribbean. It also seeks to increase the success of the restoration projects based on the principles of ecological restoration, favoring natural regeneration and succession processes before reforestation. This manual will support the development of a strategy involving proposals, planning, implementation, and follow-up of mangrove restoration programs. The manual can be used by government entities, civil organizations, the academic community, the business sector, members of civil society, indigenous peoples, and local communities.

The manual is based on the foundation of restoration ecology and ecological restoration principles of the Society for Ecological Restoration (SER, http://www.ser.org/). The ecological restoration strategy presented in this manual was developed as part of the research program of CINVESTAV-IPN Merida Unit in collaboration with the University of Barcelona, Spain; Pirenaico Institute of Ecology of the High Council of Scientific Research (CSIC, for its initials in Spanish), Spain; Scientific Research Center of Yucatan (CICY, for its initials in Spanish); UNAM-Sisal Yucatan campus; Louisiana State Univeristy, USA; Japan International Cooperation Agency (JICA); government organizations (National Commission for Natural Protected Areas [CONANP, for its initials in Spanish], National Forestry Commission [CONAFOR, for its initials in Spanish], National Commission for the Knowledge and Use of Biodiversity [CONABIO, for its initials in Spanish], Secretariat of Environment and Natural Resources [SEMARNAT, for its initials in Spanish]-Yucatan, National Institute of Ecology and Climate Change [INECC, for its initials in Spanish]), and non-governmental organizations (Ducks Unlimited de México, A.C. [DUMAC]; PRONATURA; Flora, Fauna and Culture of Mexico, A.C. [FFCM, for its initials in Spanish]).

Justification

The global loss of mangroves has escalated at an alarming pace in the past decades, reaching annual rates of 1-2% (Duke *et al*., 2007; FAO, 2007). According to the Caribbean Environment Programme of the United Nations Environment Programme (UNEP-CEP), mangroves in the Wider Caribbean region (Gulf of Mexico, Caribbean Sea and North Brazil Shelf Large Marine Ecosystems) comprise close to 26% of the global mangrove cover. They have shown a decline of 24% of their extent in the past 25 years (Wilson, 2017; De Lacerda *et al*., 2019). Within this region, the MAR (Mexico, Belize, Guatemala, and Honduras) has lost over 110,000 hectares in the past 20 years (Canty *et al*., 2018).

The loss of the mangrove cover has been caused by economic activities in the region (aquaculture and farming, forest use, tourism infrastructure, urban development, soil and water contamination) and by natural events (FAO, 2007). The consequences of these losses have been the reduction of the ecological integrity of those ecosystems and a decline of the ecosystem services they provide, at local and regional levels, which affect human well-being, food security, property, and livelihoods.

The trends of recovery and degradation reduction of mangroves in the Wider Caribbean region are not encouraging because, despite all the efforts made, only a small percentage of the degraded areas have been restored (Romañach *et al*., 2018). Regionally, efforts have been made to create an instrument containing a series of strategies and actions necessary to achieve conservation and restoration goals in the mangrove ecosystem in the MAR ecoregion, coordinated by MAR Fund (Rivas *et al*., 2020).

The next step will be to implement actions, policies, and technical strategies. One of them is the restoration of mangroves following a strategy that will maximize the success of interventions. Locally, restoration actions have been carried out, where the major activity is reforestation, yet in most cases, experience has come from trial-and-error (Rodríguez-Rodríguez, 2015; Quiro, 2017; Nello *et al*., 2018).

The outlook seems uncertain at the dawn of the United Nations Decade for Ecosystem Restoration 2021-2030 (UN, 2019) since mangrove restoration actions in the Wider Caribbean region have not been developed under a strategy or based on the principles of ecological restoration (SER 2019). Although restoration projects are socially well accepted by local communities because of the economic benefits they obtain, the ecological benefits are far less evident.

Such incentives do not ensure the long-term success of restoration; however, they represent an opportunity to keep strengthening regional protocols, national restoration and landscape strategies that include restoration actions under the Bonn Challenge, and local capacities to internalize the importance of protecting and restoring mangroves for human well-being, put forward by organizations, such as the CCAD and the four governments of the MAR countries. Therefore, this manual contributes to implementing a mangrove ecological restoration strategy that will magnify the success of the projects implemented in the Wider Caribbean region, involving and benefitting the different participating stakeholders.

1. Introduction

The Wider Caribbean region, according to the regional strategy for the protection and restoration of marine habitats (RSAP) of the Caribbean Environment Programme of the UN Environment Programme (UNEP-CEP), stretches from the United States to Brazil and the Guianas (UNEP-CEP, 2020). This region is broader than the Cartagena Convention administered Wider Caribbean region, which integrates the CLME+ region (the Caribbean and North Brazil Shelf Large Marine Ecosystems) with the Gulf of Mexico Large Marine Ecosystem (LME) (Fig. 1.1). Reef-mangrove-seagrass complexes are found across the Wider Caribbean, which play a fundamental role in the economy and well-being of over 134 million residents living in the coastal areas, especially in the developing small insular states of the Caribbean, and which strongly depend on coastal marine resources (Patil *et al*., 2016; UNEP-CEP, 2020). Located within this complex is the Mesoamerican Reef System, the largest transboundary reef in the world and one of the most biodiverse, valuable, and productive ecological systems. In the Wider Caribbean region, mangroves represent approximately 26% of the global mangrove area (De Lacerda *et al*., 2019), and are the region's economic foundation for the diversity of ecosystem services they provide to the population.

Mangroves interact with two of the most important industries of the region: fisheries and tourism, which generate USD 5 billion and USD 47 billion in revenue, respectively (Serafy *et al*., 2015; Patil *et al*., 2016; Spalding and Parett, 2019). In addition, mangroves are an important natural barrier that reduce the high vulnerability of the region's coastlines during hydrometeorological events such as hurricanes, with an estimated value of USD 23,000 to 45,000 per hectare, just in the Caribbean (Beck *et al*., 2020).

Furthermore, they represent a critical blue carbon sink (Donato *et al*., 2011), a key component of international agreements in reducing greenhouse gases (GHG) through programs like REDD+ and carbon markets, including them in nationally determined contributions, in compliance with the Paris Agreements (NDCs; UNFCCC, 2016).

Despite their importance, mangroves in the Americas and the Caribbean have shown a decline of 24% in the past 25 years (Wilson, 2017; De Lacerda *et al*., 2019). Overexploitation of resources, pollution, disorganized land use change, and the effects of climate change, such as sea level rise, are some of the main drivers for mangrove degradation (Ellison y Farnsworth, 1996; Lugo, 2002; DeLacerda *et al*., 2019). The loss of mangrove cover in the Caribbean region has resulted in economic losses, and an increased hurricane exposure has jeopardized the human well-being, food security, property, and livelihoods of coastal communities. Just for the MAR region, a 30% reduction of the mangrove range has been estimated between 1990 and 2010, amounting to an economic loss of approximately USD 602,157,600 per year (Canty *et al*., 2018; Rivas *et al*., 2020).

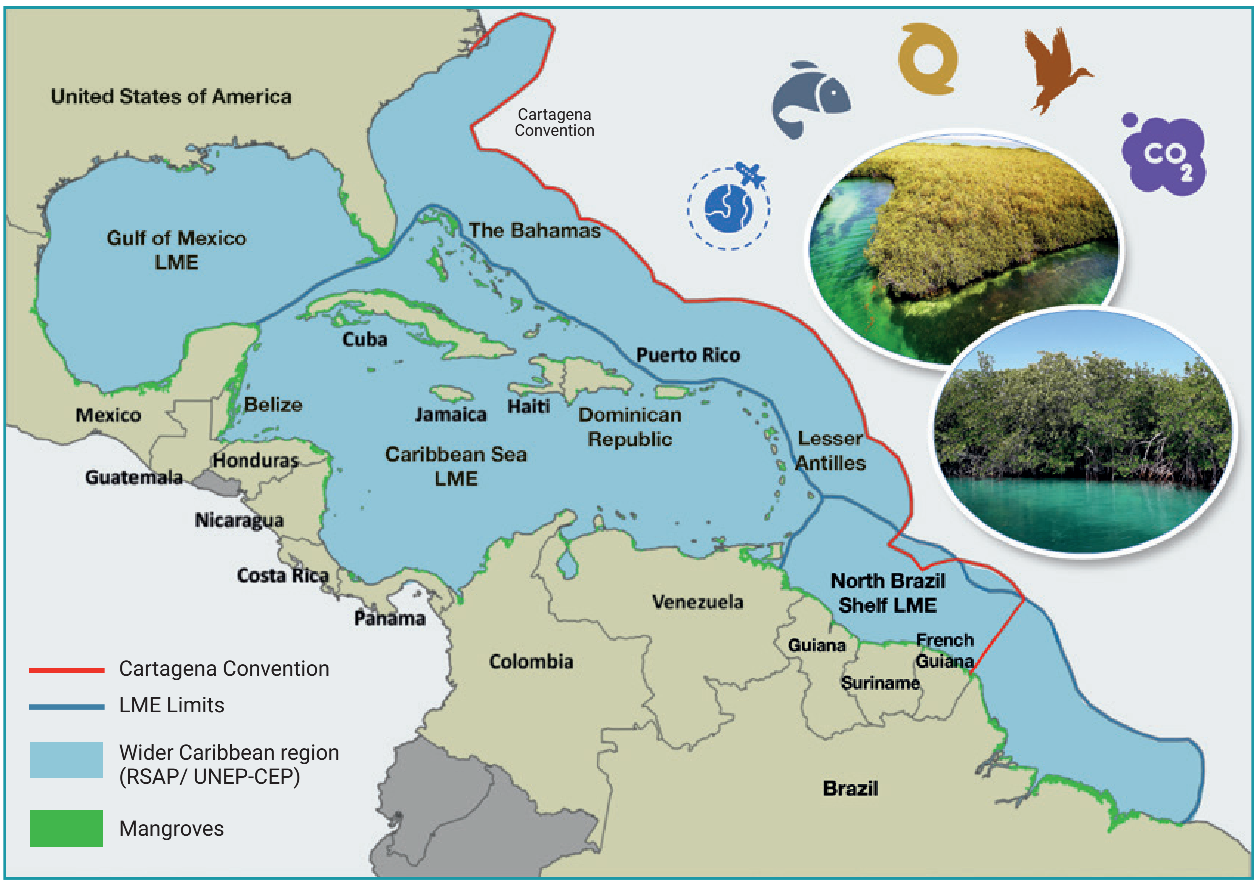


Figure 1.1. Distribution of mangroves in the Wider Caribbean region, comprised of the Large Marine Ecosystem (LME) of the Gulf of Mexico, the Caribbean Sea, and North Brazil Shelf, according to the Regional Strategy and Action Plan for the Valuation, Protection and/or Restoration of Key Marine Habitats in the Wider Caribbean 2021-2030 (RSAP) of UNEP-CEP (2020). Prepared by Pedro J. Robles-Toral and Diana J. Cisneros.

Based on the above, the conservation and restoration of mangrove ecosystems is a priority within the Wider Caribbean region. To this end, several strategies have been developed (Fig. 1.2), particularly the one being coordinated by MAR Fund for the MAR ecoregion (Rivas *et al*., 2020) and the Regional Strategy and Action Plan for the Valuation, Protection and/or Restoration of Key Marine Habitats in the Wider Caribbean 2021-2030 (RSAP), developed under the subprogram SPAW of the Cartagena Convention. Within the framework of this Convention and the UN Decade on Restoration, mangrove restoration is considered a Nature-based Solution (NbS) that addresses the effects of climate change, the conservation of biodiversity, and the economic and social well-being of populations, as well as contributing to the Sustainable Development Goals.

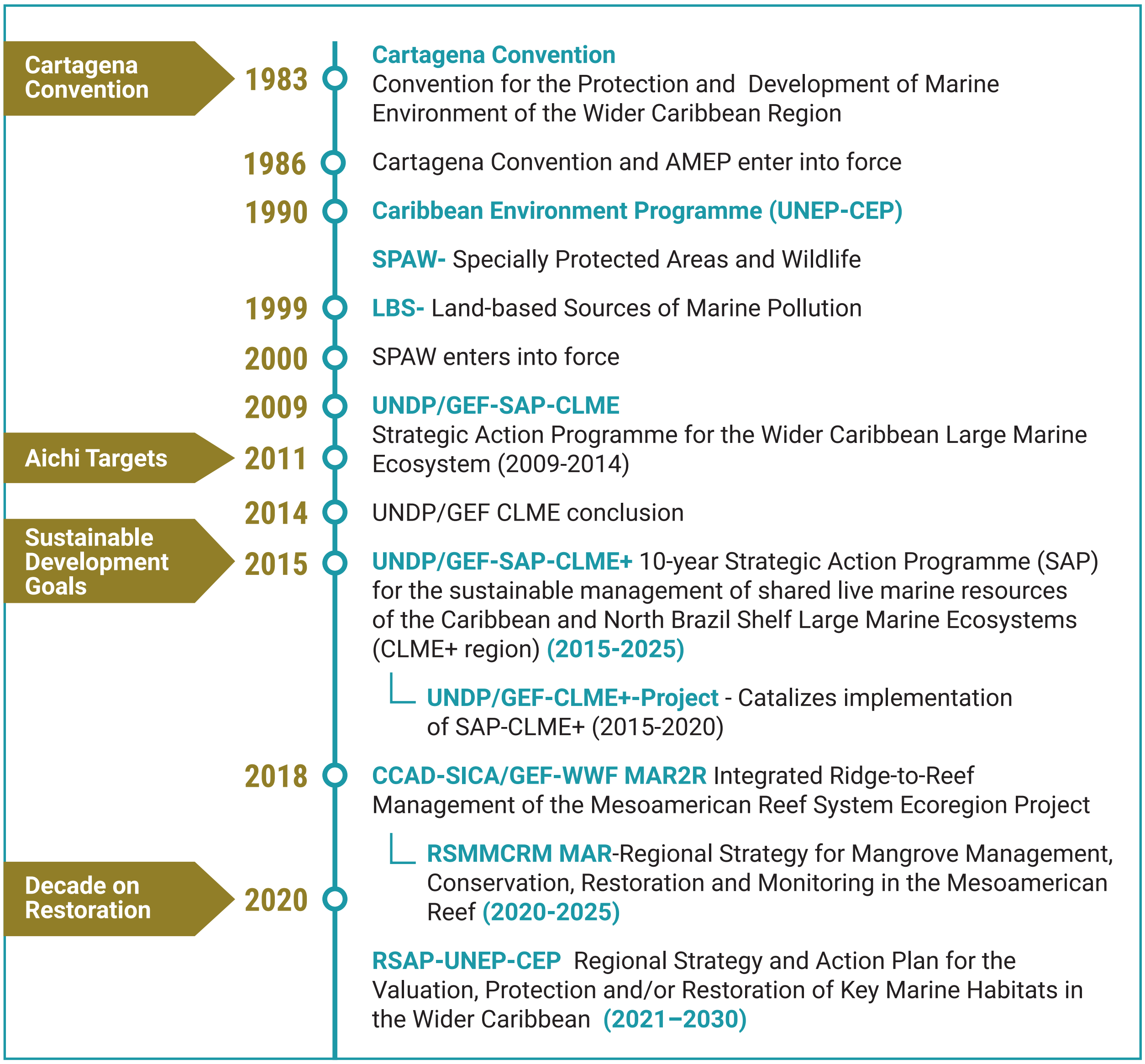


Figure 1.2 — International efforts on mangrove conservation and restoration in the Wider Caribbean region.

According the Global Mangrove Watch, the Wider Caribbean region suffered an estimated 304,715 ha of mangrove loss and degradation, of which at least 680 sites have the potential of being restored (www.globalmangrovewatch.org/), but only a small percentage of the degraded areas have been recovered (Romañach *et al*., 2018).

In order to fulfill the objectives of the regional strategies and international agreements, it is necessary to implement actions that maximize the success of restoration interventions in the MAR and the Wider Caribbean. The goal of this manual is to contribute to the strengthening of local and regional capacities for the ecosystem mangrove restoration and increasing the success of the implemented projects by involving and building agreements between the participating stakeholders. The strategy presented in this manual is based on the integration of ecological, economic, and social components, supported with scientific knowledge and lessons learned, and shared with coastal communities.

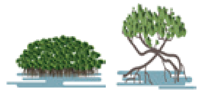
1. Mangroves of the Wider Caribbean

Nine species, from the nearly 70 mangrove species existing globally, have been recorded in the region to date. The most widely distributed species, both in the continental and insular part of the region, are *Rhizophora mangle, Laguncularia racemosa, Avicennia germinans*, and *Rhizophora harrisonii* (Fig. 1.3). These species can occur as trees or shrubs in response to particular environmental conditions in which they are found. Environmental conditions are related to three main factors: climate, hydrology, and geomorphology at a regional level, and soil type, topography, and nutrient availability at a local level (Twilley *et al*., 1998).

The interaction between these factors results from a wide variety of mangrove composition and structure, described by Lugo and Snedaker (1974) as different mangrove ecological types. These mangrove types can have tall, dwarf, dense, disperse, mono-, and multi-species structures. This variability in structure and composition favors, in turn, to the diversity of ecosystem services that they provide.

Rhizophora mangle

Red mangrove
American mangrove



USA to BRA and ANT

Fresh | Brackish | Hypersaline

Avicennia germinans

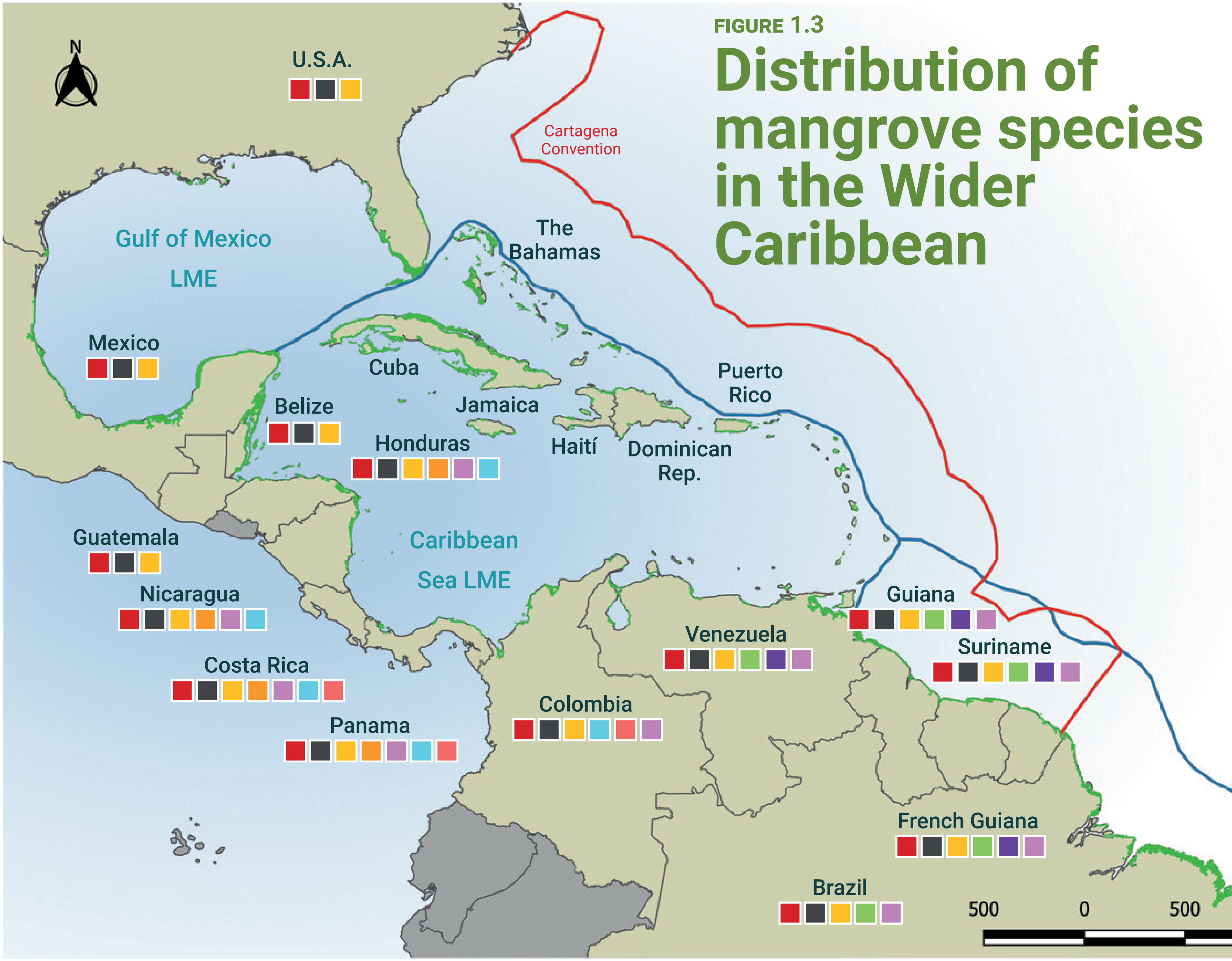
Black mangrove

USA to BRA and ANT

Fresh | Brackish | Hypersaline

FIGURE 1.3

Distribution of mangrove species in the Wider Caribbean



Rhizophora racemosa

White mangrove

HON to BRA and ANT

Fresh | Brackish | Hypersaline

Avicennia schaueriana

Black mangrove

VEN to BRA

Fresh | Brackish | Hypersaline

Laguncularia racemosa

White mangrove

USA to BRA and ANT

Fresh | Brackish | Hypersaline

Rhizophora harrisonii

In Spanish: mangle zapatero, mangle caballero

VEN to GUF

Fresh | Brackish | Hypersaline

Hectares of lost and degraded mangrove

Cartagena Convention	238,116
Caribbean Sea LME	75,884
Gulf of Mexico LME	142,335
North Brazil Shelf LME	86,496

Mangrove sites with restoration potential

Cartagena Convention	664
Caribbean Sea LME	526
Gulf of Mexico LME	97
North Brazil Shelf LME	57

United States of America - USA
Mexico - MEX
Honduras - HON
El Salvador - SLV
Nicaragua - NIC
Costa Rica - CRI
Panama - PAN
Colombia - COL
Ecuador - ECU
Venezuela - VEN
French Guiana - GUF
Brazil - BRA
Antilles - ANT

Tree | Shrub

North Brazil Shelf LME

Avicennia bicolor

In Spanish: Mangle salado

SLV to PAN

Fresh | Brackish | Hypersaline

Pelliciera rhizophorae

Tea mangrove

NIC to COL

Fresh | Brackish | Hypersaline

Mora oleifera

In Spanish: alcornoque

CRI to ECU

Fresh | Brackish | Hypersaline

Prepared by Pedro J. Robles-Toral, Andrés Canul-Cabrera and Diana J. Cisneros.

Of the total area of mangroves in the Wider Caribbean region (2,616,312 ha), approximately 204,330 ha correspond to degraded or deforested areas. In these areas, 680 sites are reported to have restoration potential (Global Mangrove Watch, 2021). North and Central America has the highest percentage of mangrove loss, while the Lesser Antilles has a smaller area, but with a higher conservation percentage (Fig. 1.4).

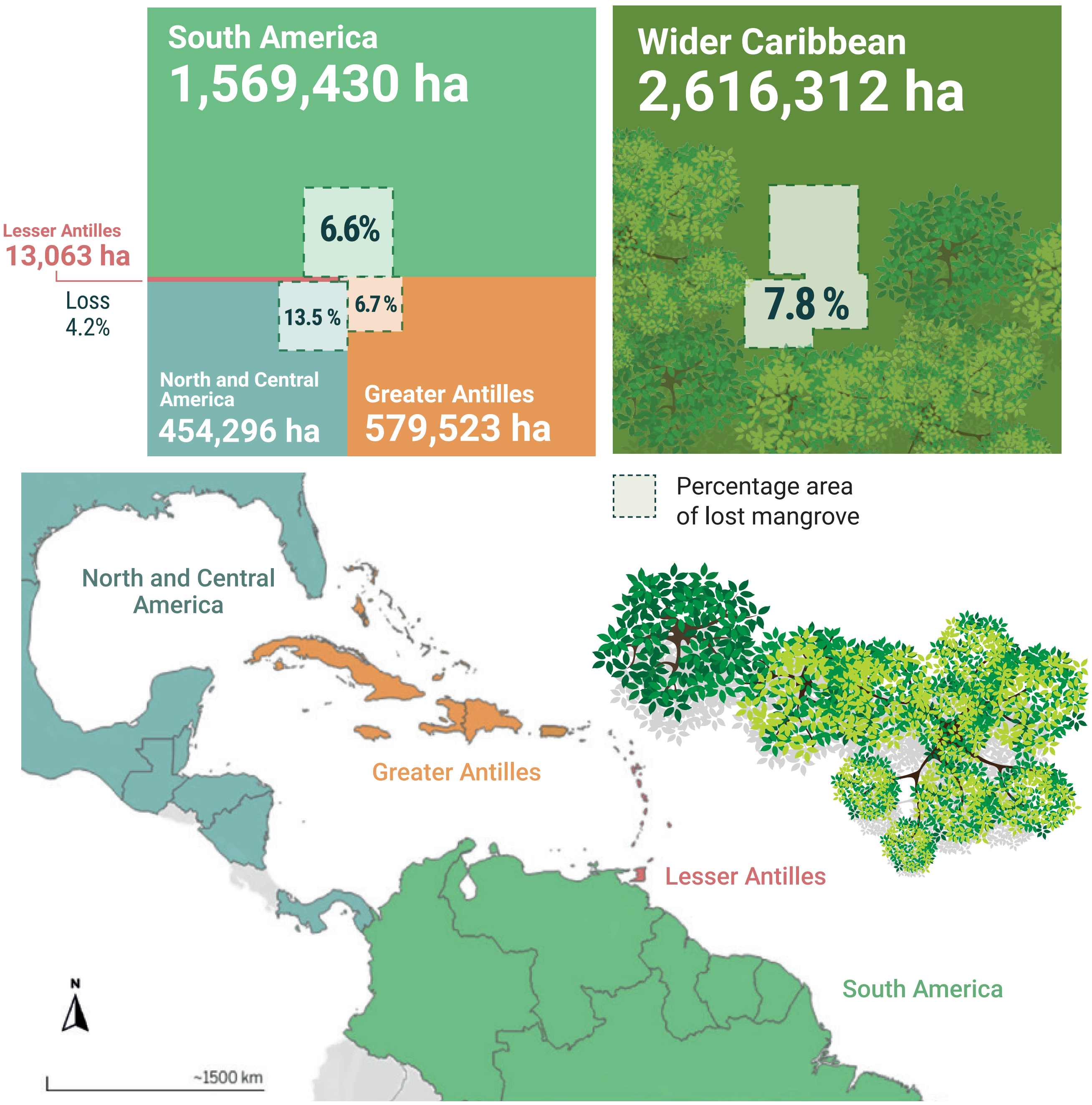


Figure 1.4 — Total area of mangrove in the Wider Caribbean region and sub-regions with their corresponding area percentages of lost mangrove with restoration potential. Prepared by Pedro J. Robles-Toral, Andrés Canul-Cabrera and Diana J. Cisneros.

2. Ecological Restoration

Ecological restoration (ER) can be defined as the process of recovering a degraded, damaged, or destroyed ecosystem in order to obtain values marked as intrinsic to the ecosystem and to provide goods and services valued by the population (Martin, 2017).

This definition broadens and improves the description by SER (2002) because it includes social and economic factors inherent to ecological restoration. The ER serves as an activator to initiate or accelerate a process that favors the recovery of a mangrove ecosystem, considering its short-, medium-, and long-term recovery.

Both in theory and practice, the recovery of the ecosystem's basic structure and key functions is essential to continue its self-organization. Social and economic aspects must be considered in any kind of restoration and any site intended for restoration so that the project is socially acceptable and financially feasible. Including scientific-technical, social, and economic aspects are part of developing the theoretical basis derived from hands-on experience in restoration (Fig. 1.5) (Comín *et al*., 2005).

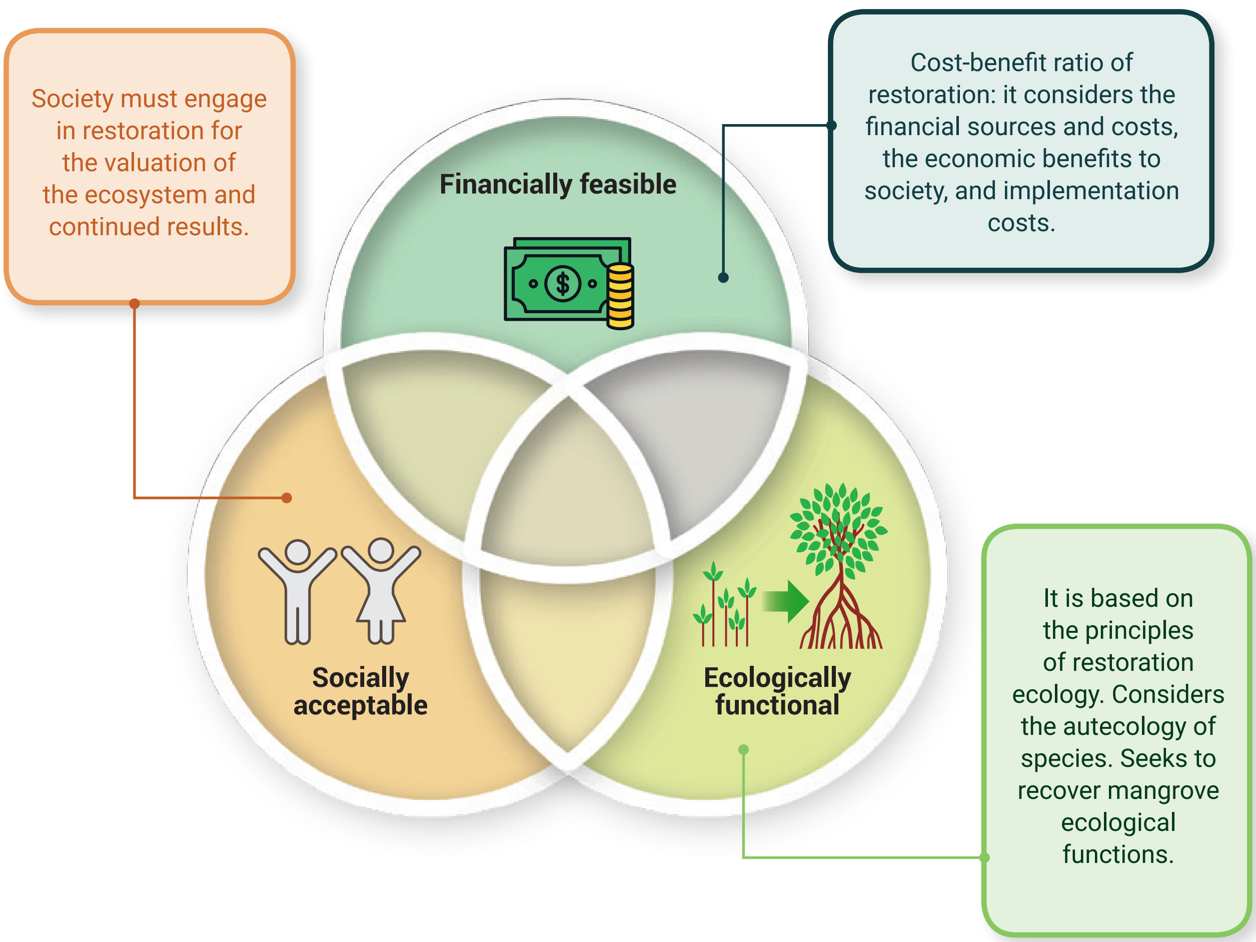


Figure 1.5 — Elements to consider during the ecological restoration.
Modified from Teutli-Hernández, 2017.

Temporal and spatial scales are two of the most important aspects to consider in the planning and implementation of ecosystem restoration because processes take place at different spatial (from centimeters to hectares) and temporal scales (from hours to decades). There are also anthropogenic stressors which cause changes at different natural scales of time and space and affect ecological processes. In the case of coastal sediment ecosystems, such as mangroves, the coastline evolves throughout time, showing variations at annual, decadal, and longer periods. Yet, time is a factor usually not considered in restoration projects (Comín *et al.*, 2004) (Fig. 1.6).

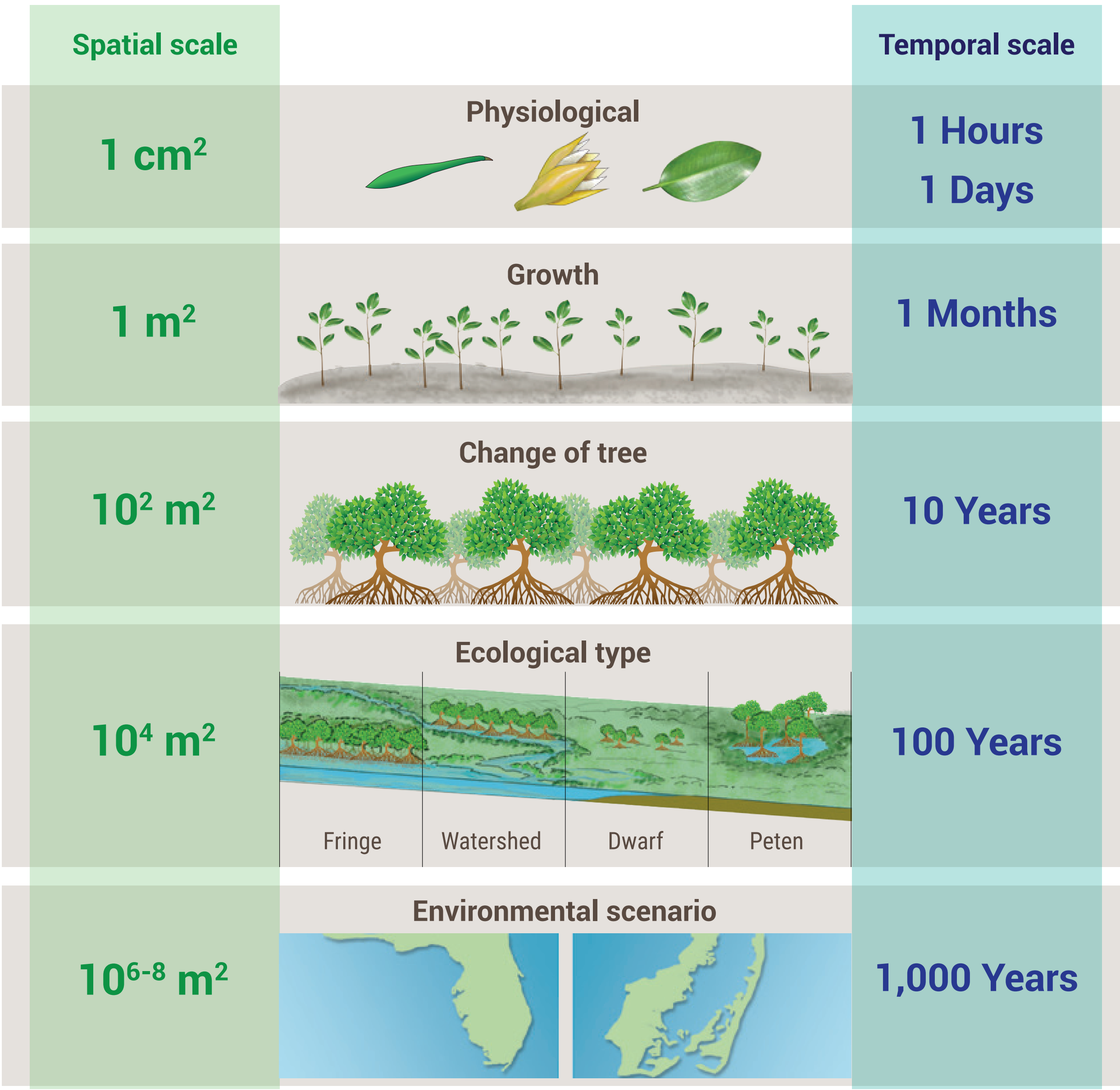


Figure 1.6 — Temporal and spatial scales to consider in the mangrove ecological restoration. Modified from Twilley *et al.*1999.

It is essential to consider the spatial scale because mangrove ecosystem function is closely related to other coastal ecosystems: from the open sea to inland watersheds. Among these systems, there are exchanges of matter and energy with water flows and sediment transport. These exchanges can contribute to the mangrove ecosystem recovery without other intervention than enabling some of these flows (passive restoration). At a larger spatial scale of restoration (>100 ha), a passive restoration (reactivation of water flow) is preferable since the mangrove ecosystem is self-organizing in relation to other neighboring ecosystems.
At smaller spatial scales, active restoration (reforestation, topographic modifications) may prove more effective, which, in addition to enabling the water flow, consists of active revegetation with plants, using adequate techniques and knowledge of the autecology of species (Fig. 1.7).

Passive restoration

Consists of removing factors that lead to degradation or destruction. It is focused on improving the eco-hydrological processes for the reconstitution of the hydro-geomorphology and self-replenishment of the biological community, promoting the natural dynamics of the ecosystem (Simenstad *et al*., 2006; Zhao *et al*., 2016).

Active restoration

It requires a physical intervention with engineering actions to intentionally and specifically re-create the wetland structure and process, in order to restore, regenerate, or improve the community structure and wetland processes (Simenstad *et al*., 2006; Wagner *et al*., 2008).

Figure 1.7 — Types of restoration according to the type of implemented restoration actions. However, today it is proposed to forget the dichotomy between passive and active restoration and admit a continuum of restoration actions (Chazdon *et al*., 2021).

The connection between mangroves and other land and marine ecosystems suggests that the spatial scale of restoration of the entire coastal area may be the most suitable for recovering the degraded ecosystems and the goods and services they provide (Fig. 1.8).

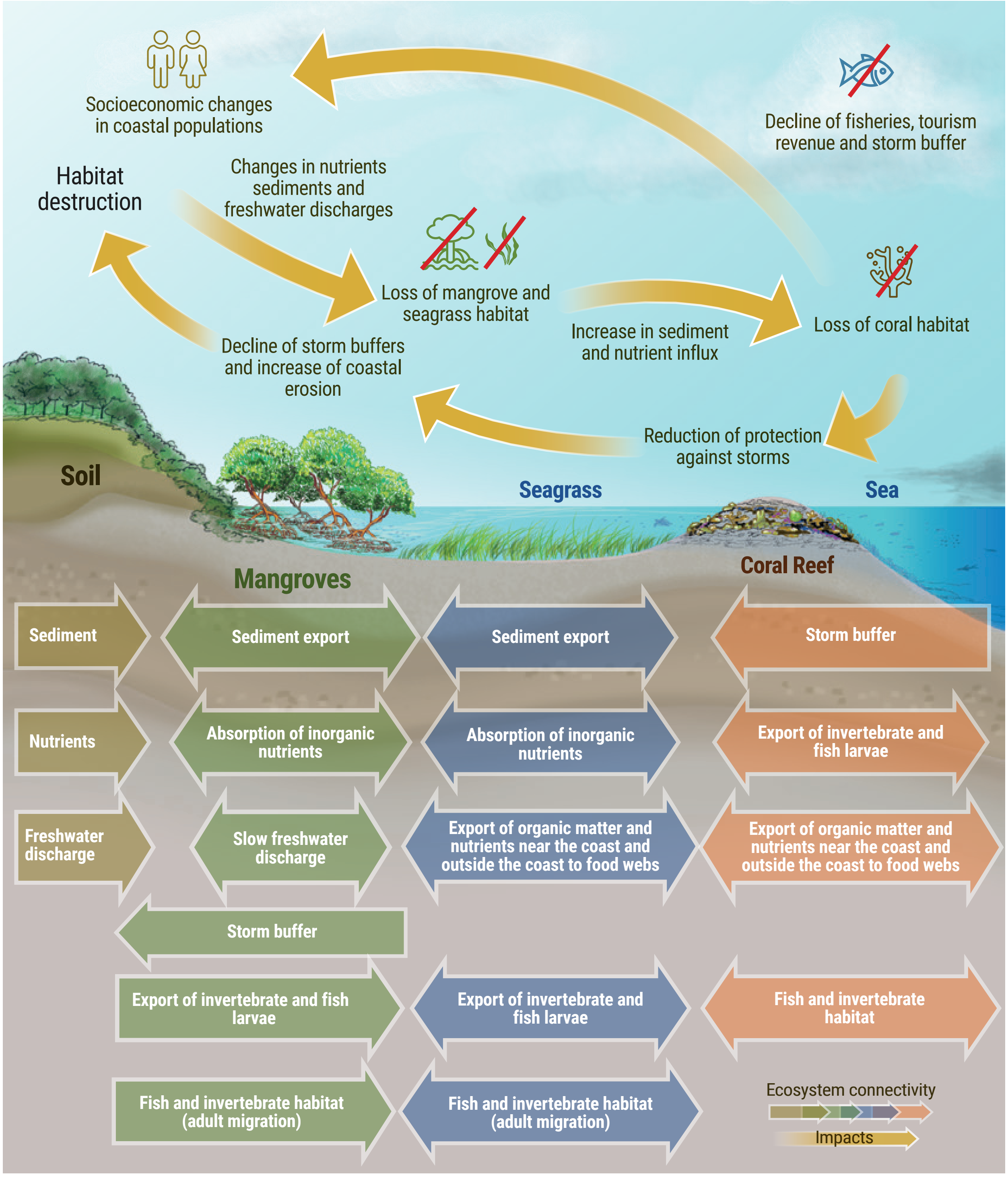


Figure 1.8 — Flowchart of the connectivity between mangrove, seagrass and coral reef ecosystems. Physical and ecological connectivity between ecosystems is represented for each ecosystem: land-based (brown arrows), mangroves (green arrows), seagrass (blue arrows), and coral reefs (red arrows). Possible feedback through ecosystems and impacts of different human activities in ecosystem services (yellow arrows). Modified from Silvestri and Kershaw (2010).

2. Mangrove ecological restoration

The strategy to carry out a mangrove ecological restoration project developed in this manual is based on the international standards and principles of the Society for Ecological Restoration (SER, 2004; Gann *et al*., 2019). At the core it is about establishing institutional arrangements and agreements to strengthen the group's governance (working group) and provide accountability of actions and responsibilities of each party during the restoration process, thus securing economic sustainability and long-term continuity of the restored ecosystem.

It also considers a multidisciplinary approach that includes social, ecological, and economic components so that the project is based on ecological foundations, is financially feasible, and is socially acceptable. In order to achieve this, the engagement and representativeness of local communities (social component), the scientific-technical working group (academics and professionals), the economic as well as the legal components, and the inclusion of authorities and funders is essential throughout the restoration process.

The strategy is outlined in six main steps that include social, ecological, and economic components (Fig. 2.1).

Figure 2.1 — Mangrove ecological restoration strategy (modified from Teutli-Hernández and Herrera-Silveira, 2016).

1 Setting up the working group

Mangrove restoration is a collaborative effort within which different sectors are involved in order to have adequate governance and cohesion throughout the project. It is recommended that the technical group includes local community members, organized social groups, indigenous peoples, civil organizations, academics and professionals, environmental managers, and representatives of funding sources. Each sector brings different strengths to the project for its implementation (Fig. 2.2).

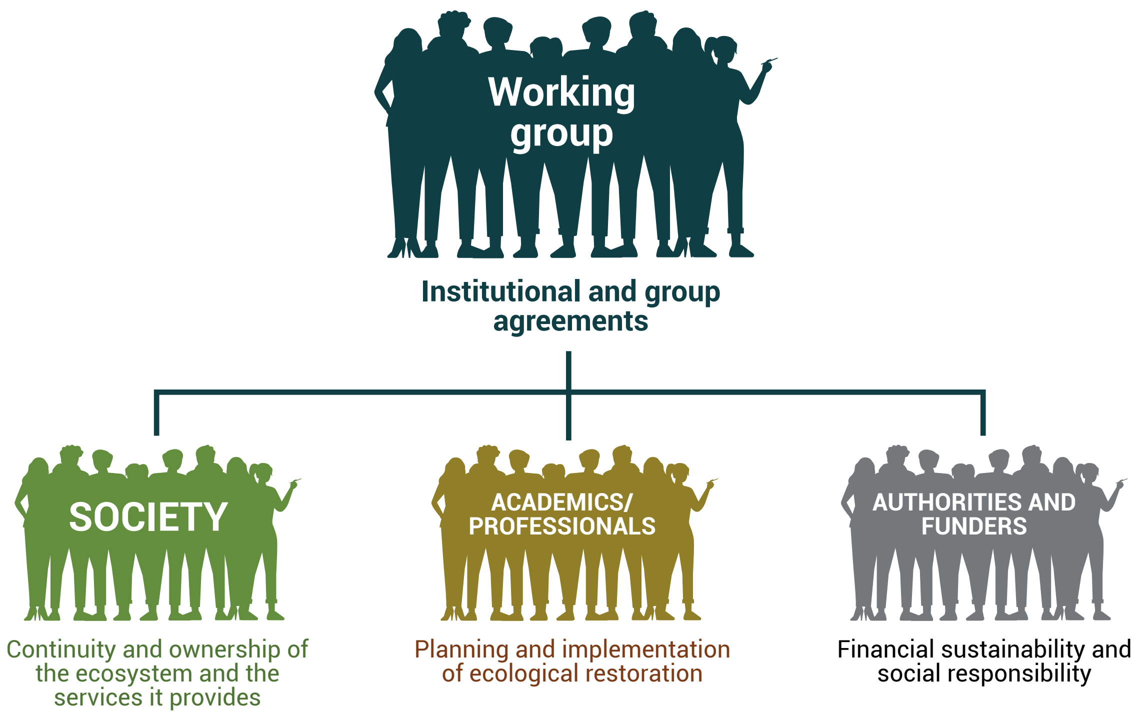


Figure 2.2 –Different sectors of society take part in the working group to strengthen institutional agreements during restoration. Prepared by Diana J. Cisneros.

First and foremost, the participation of **society** (local communities, indigenous peoples) is critical. It should be included early, from planning to implementing and monitoring restoration projects, since society benefits the most from the outcomes. This is because communities live directly in or in close proximity to mangroves, so they are able to provide valuable local information about the site and good resource management. For this reason, every restoration project must involve local knowledge and traditions and the interest of society, and integrate these components into restoration objectives. The acceptance and participation of local communities are fundamental for the long-term continuity of projects by owning the site from which they obtain multiple benefits.

Academics and professionals make up the technical-scientific working group responsible for applying scientific principles during restoration, as well as implementing the practice of ecological restoration and its theories. Therefore, restoration actions are based on the knowledge of geomorphology, hydrology, and structural and functional characteristics of the mangrove ecosystem at different spatial and temporal scales. Restoration sites become natural laboratories that strengthen or generate knowledge, which improve current techniques, as well as contributing to capacity building of communities, including community monitoring, which consolidates the ownership of the site and the continuity of the associated benefits.

Authorities and funders are the group in charge of securing the financial resources to implement restoration, as well as handling the legal (permits of the area to be restored) and administrative aspects required for the restoration project. Their participation allows for restoration to impact public policies and global, regional, and national goals. This is possible only if there is adequate communication and dissemination of the process and the project's results. The participation of civil organizations is vital because they bring financial certainty to the project. At the same time, they contribute to promoting social well-being, representing and connecting the project's objectives to local and regional needs.

The responsibilities of each working group member and the level of participation must be established early on in order to create institutional or group agreements and arrangements, which are then fulfilled throughout the restoration process and promote the long-term success and viability of the project. It is not always possible to consider the participation of all stakeholders from the beginning of the project. However, their participation must be encouraged throughout the restoration process through workshops, training, and adequate communication of the project, highlighting the benefits for each sector involved.

Participation of academia, institutions, and society in the working groups of mangrove restoration in Sian Ka'an, Quintana Roo, Mexico.

2 Site identification and defining the objectives and goals

Selecting the site must always be based on the needs of the community and the ecosystem services they would like to be recovered. The area can be defined by all the groups (i.e., society, funders, academics). One tool that can be used to delimit a site to be restored is the mangrove restoration potential map, available at http://oceanwealth.org/mangrove-restoration/, with which potentially restorable areas can be identified (Worthington and Spalding, 2018).

Preserved nearby site
Allows to ensure the availability of propagules and seeds as to avoid the use of nurseries, thus reducing restoration costs.

Close water source
Locate water sources (fresh/brackish/saline), to allow the desalinization of the site or salinization, depending on the case.

Accesibility to the site
Consider time and cost of trips, easy to locate, the site may be used for demonstration and training.

Benefits to the community
Direct benefits to the community (fisheries, wood, apiculture, etc.).

Secured funds and amount
The amount of funds is related to the accessibility of the site, the area, the extent of damage, among others.

Safety
Avoid putting people involved in danger during restoration actions at the selected sites.

Authority permits and community consent
Obtain the authority's permit and the native community's consent before starting restoration projects.

Connection with other projects
Exchange of experiences and information of implemented projects.

Anthropogenic stress factors
Anthropogenic stressors of the site and the change in soil use must be considered for the long-term viability.

Land ownershipand protection status
There must be some kind of legal security that allows the restoration and its benefits to endure.

Objective of the area to be restored
The area must be suitable for the objective to be achieved.

Extent of disturbance
To be considered according to the resources available and the cost of the actions neces-sary for its recovery.

Opportunity for science and civic education
What is the learning and research potential with the development of the project.

Figure 2.3 — Criteria to consider during the identification and delimitation of the site to be restored.
Prepared by Eunice Pech and Diana J. Cisneros.

However, while using this tool, it is important to consider the scale to be used because it does not always reflect the site's specific characteristics at regional and local levels. Therefore, it must be verified directly with field data collected at the chosen location. Additionally, it is important to consider the political, economic, ecological, and social criteria when selecting a site to ensure the viability, implementation, and sustainability of restoration outcomes (Fig. 2.3). It is important to determine, if available, a good reference site as the goal to be achieved or replicate as much as possible through ecological restoration. If a suitable site is not available, a review of the literature and historical data of the site (species, environmental conditions, etc.) must be conducted to understand what can be achieved through restoration.

The objective of the restoration project must be acheivable and measurable, this can be either an ecological or social approach, or both, and respond to questions, such as "What needs to be recovered?" The community, the vegetation, fish populations, reduction of salinity in sediment, water flow, coastal protection, etc. "Why does it need to be restored?" It might be to recover the crab community for bait, recover the bird community, recover the habitat of commercially important aquatic species, or a specific ecosystem service, or solve a social issue (e.g., create temporary jobs with actions). "How much will it cost?" In this regard, implementors must consider developing workshops, payment of daily wages for the community involved in restoration actions, sampling equipment for the implementation of restoration actions, and safety gear. Also, a budget for monitoring restoration must be considered, as well as sharing the lessons learned during the restoration process. "Who will implement and coordinate the restoration?", "How is the restoration going to be assessed?" etc.

In order to answer these questions, specific short-, medium-, and long-term goals and objectives must be set (Fig. 2.4).

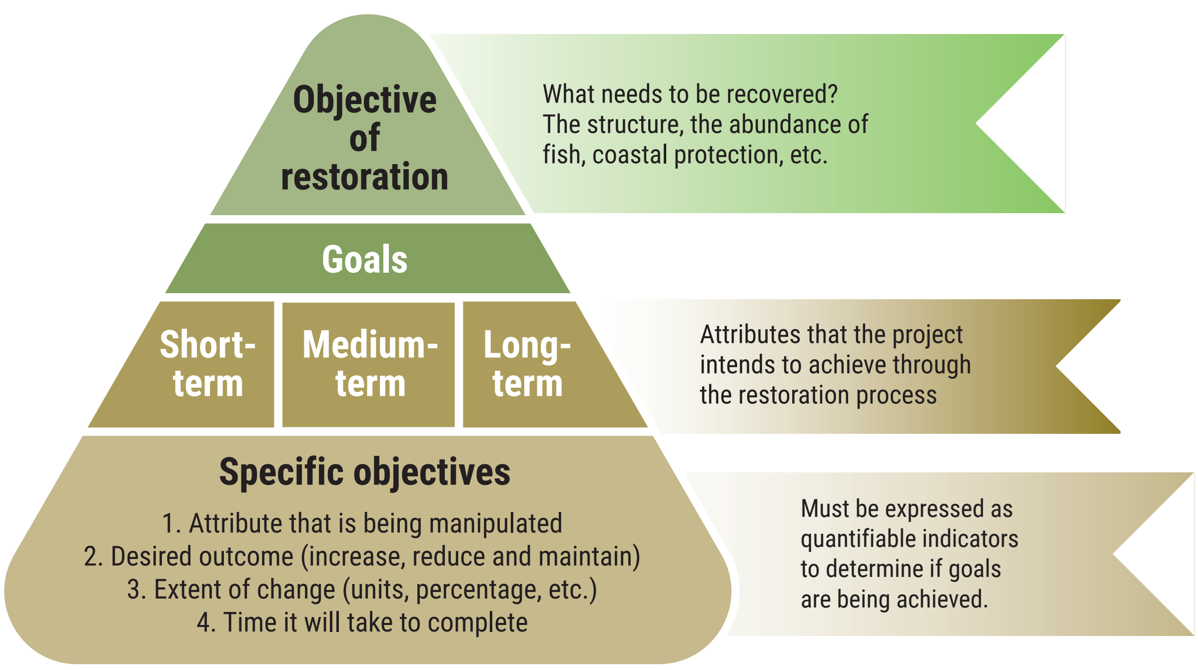


Figure 2.4 — Characteristics of goals and objectives in mangrove restoration.
Prepared by Diana J. Cisneros.

Goals determine the condition or state of the ecosystem and the attributes that the project intends to achieve with the restoration process. These will be met through specific objectives, which must always be expressed in quantifiable indicators to ensure whether the project is accomplishing the goals set out within the established timeframes (Table 2.1). This makes it possible to assess the restoration progress and, if necessary, to make changes under an adaptative management approach.

TABLE 2.1 — Example of goals and objectives set for mangrove ecological restoration

Objective	Goals	Specific objectives	Indicator
Restore 36 ha of degraded mangrove.	Establish mangrove seedlings by restoring the hydrology and the reduction of interstitial salinity.	Reduce the interstitial salinity to 50% in 18 months.	Salinity.
		Favor the natural regeneration in 18 months.	Number of seedlings.
		Synchronize water level variations between the built canal and the reference canal in 6 months.	Frequency, level, and duration of the flood.

3 Forensic Ecology

Every restoration project must begin with a diagnostic that allows for the identification of the cause or causes of mangrove degradation or loss and determine the current environmental conditions of the site. Forensic ecology is the diagnostic of the site to be restored, that uses the current and historical ecological and social characteristics of the site, which includes measuring multiple variables related to geomorphological and hydrological characteristics, physicochemical parameters, and historical changes of the social and institutional context of the site (Fig. 2.5).

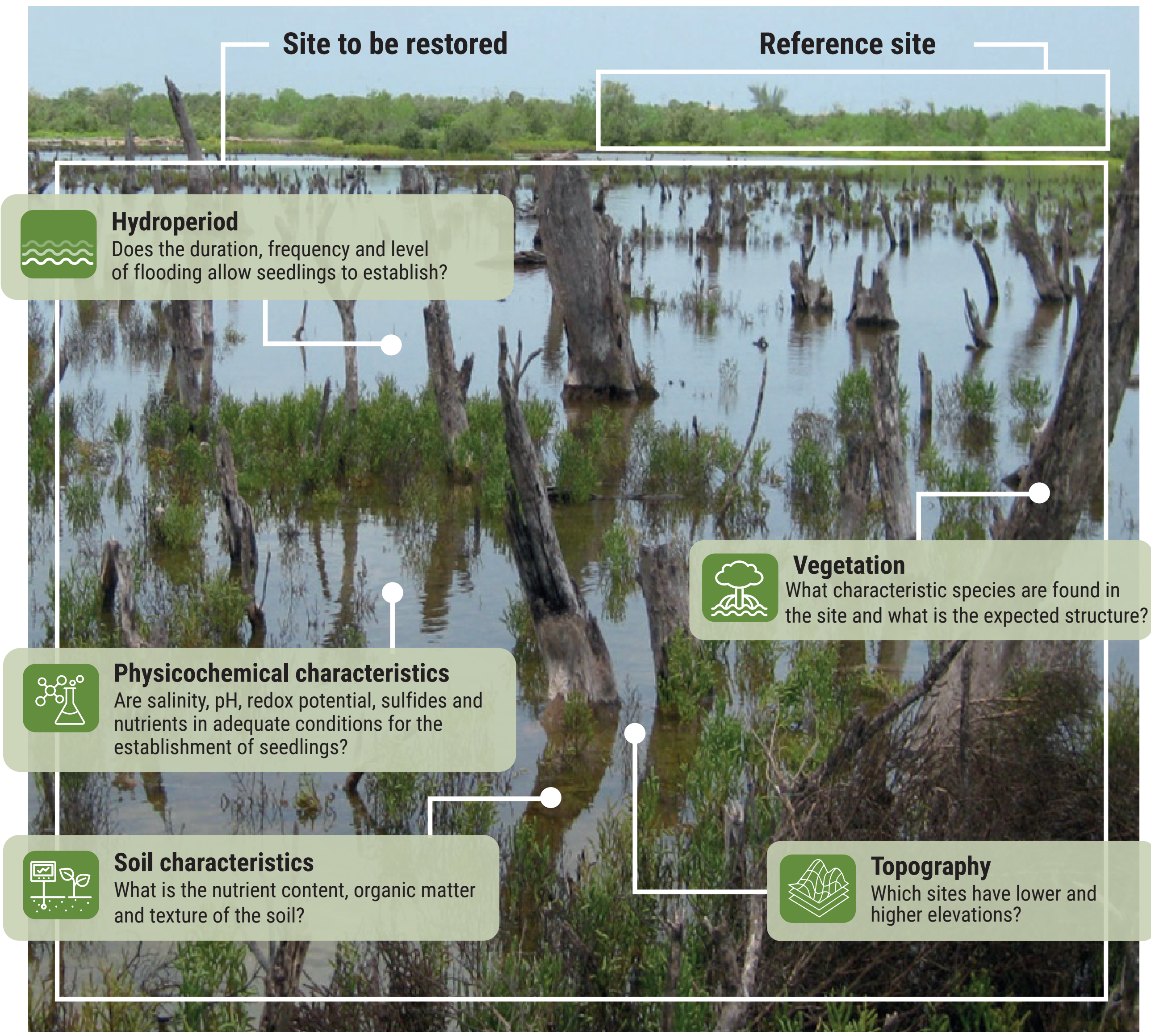
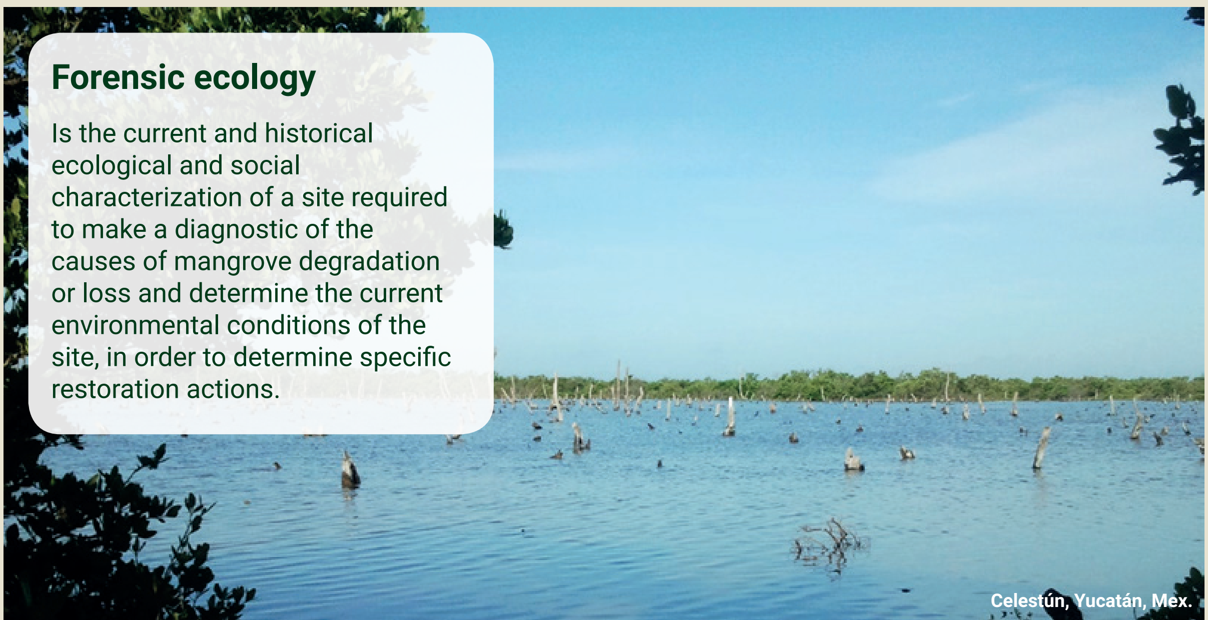


Figure 2.5 — Environmental considerations in forensic ecology for a diagnostic and charactarization of the site. Prepared by Diana J. Cisneros.

The analysis of a preserved site used as a reference of a site in good condition must be considered (Text box 2.1). This site will provide an approximation of the condition of the site to be restored prior to degradation, and represents the state towards which restoration will be measured. If there is no reference site available nearby, it will be necessary to establish references indicators based on the literature and historical research about the site and the experience from implementors. It is also recommended to consider a degraded site as a reference that has not, and will not receive intervention, and that is assessed at the same time as the reference site in good condition and the site to be restored. This allows results from restoration actions to be established, as well as to evaluate the resilience of the site if it has undergone a natural recovery.

TEXT BOX 2.1



Forensic ecology

Is the current and historical ecological and social characterization of a site required to make a diagnostic of the causes of mangrove degradation or loss and determine the current environmental conditions of the site, in order to determine specific restoration actions.

Celestún, Yucatán, Mex.

Preserved reference site

Allows to obtain an approximation of the condition before degradation and represents a desired final state after restoration.

Forensic ecology includes a background investigation of projects previously carried out at the site, current and historical land ownership and use, identify the presence of indigenous peoples, local communities and traditional communities, and the economic activities taking place in the area, as well as current and historic impacts to the site. In order to make an ecological characterization of the site, certain variables are considered, such as micro-typography, hydrology, water physicochemistry (interstitial/superficial), soil properties, and vegetation structure. Measurements must be made at the good reference site, degraded reference site, as well as on the site to be restored.

The specific variables to be measured during the forensic ecology must be defined according to the restoration goals and objectives set by the working group. The measurements recorded during the ecological characterization of the site allow a baseline condition of the sites to be established, which allows for future changes as a result of restoration to be monitored and quantified (see Chapter 2.5). In order to have visual monitoring, it is recommended to have fixed points established across the area to be restored to carry out photographic monitoring. This allows for restoration progress to be displayed visually to decision makers or potential funders to continue the project (Fig. 2.6).

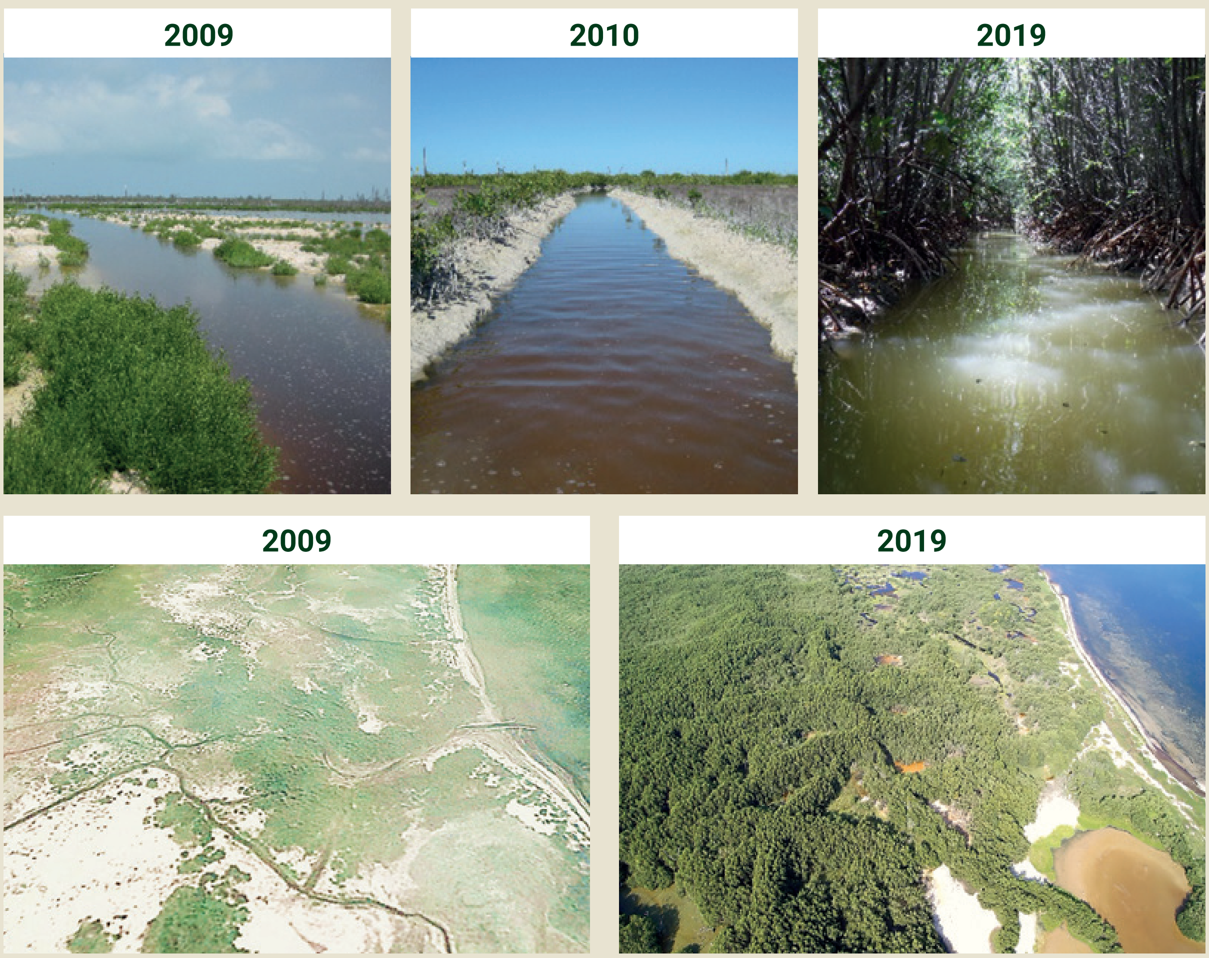
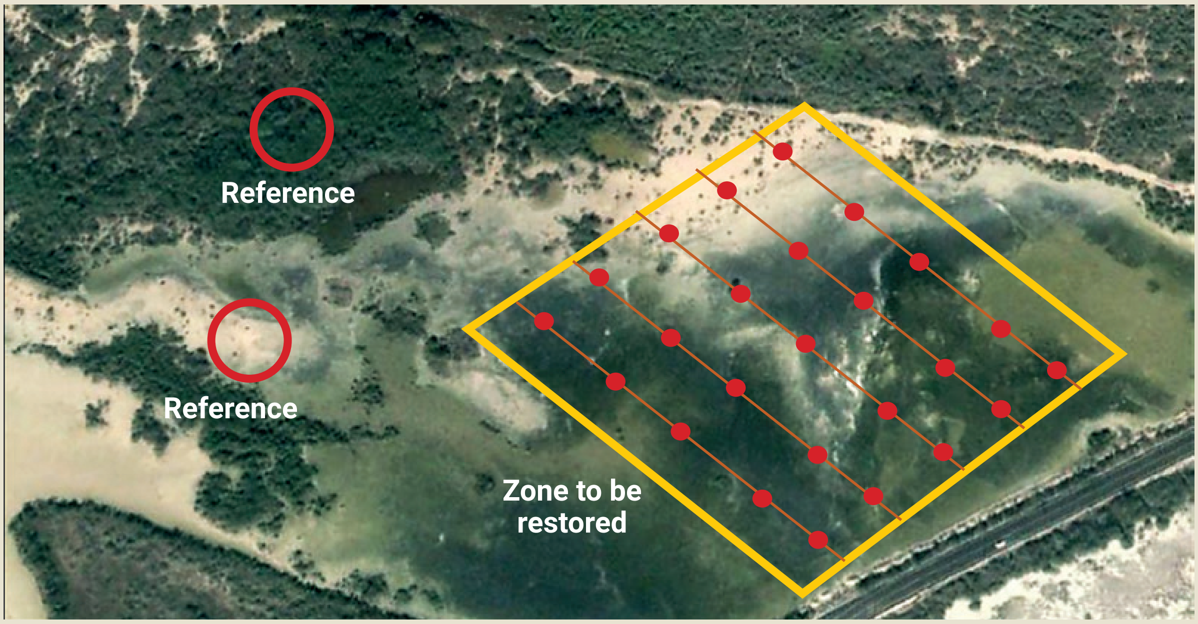


Figure 2.6 — Example of *in situ* photographic monitoring at the restoration site in Celestún, Yucatán, Mexico (above), and with aerial images in Dzilam, Yucatán, México (below).

It is recommended to conduct a landscape scale analysis with aerial photographs and satellite imagery to identify possible causes of degradation at the site, as well as to determine the points of access and establish the sampling points. For the ecological component, the sampling depends on the available resources and the project objectives. However, systematic sampling is recommended by establishing transects with equidistant sampling points that can describe the environmental heterogeneity of the site (Fig. 2.7). At every sampling point, ecological variables will be measured to create a data matrix representing the hydrological, topographical, and physicochemical differences of the site. With this information, a site-specific action plan can be developed.

The sampling stations established during the forensic ecology will allow setting permanent points for data collection and sampling to monitor indicators that will evaluate the progress of the restoration project.



Aerial photographs are used to delimit the site and sampling points

Figure 2.7 — Example of the selection of reference sites and sampling design of the area to be restored for the characterization of the site, using satellite and aerial imagery. Photos: Progreso, Yucatán, Mexico.

Ecological components and the importance of considering them during the forensic ecology for the characterization and diagnostic of the site are explained below. The different variables have different methodological options and references all of which need to be taken into consideration according to the objectives and budgets. However, it is necessary to consider some basic supplies for sampling the site during the forensic ecology and monitoring phases, which can be adjusted according to the available resources for the project (Text box 2.2).

TEXT BOX 2.2 — Basic supplies for sample collection in mangroves

In the development of a mangrove restoration project, the availability of resources may represent a challenge during the forensic ecology sampling and monitoring. This is why there are different ways to measure ecological variables.

Here is a toolkit and basic supplies for field sampling, which can be replaced by specialized equipment and tools depending on the available resources.

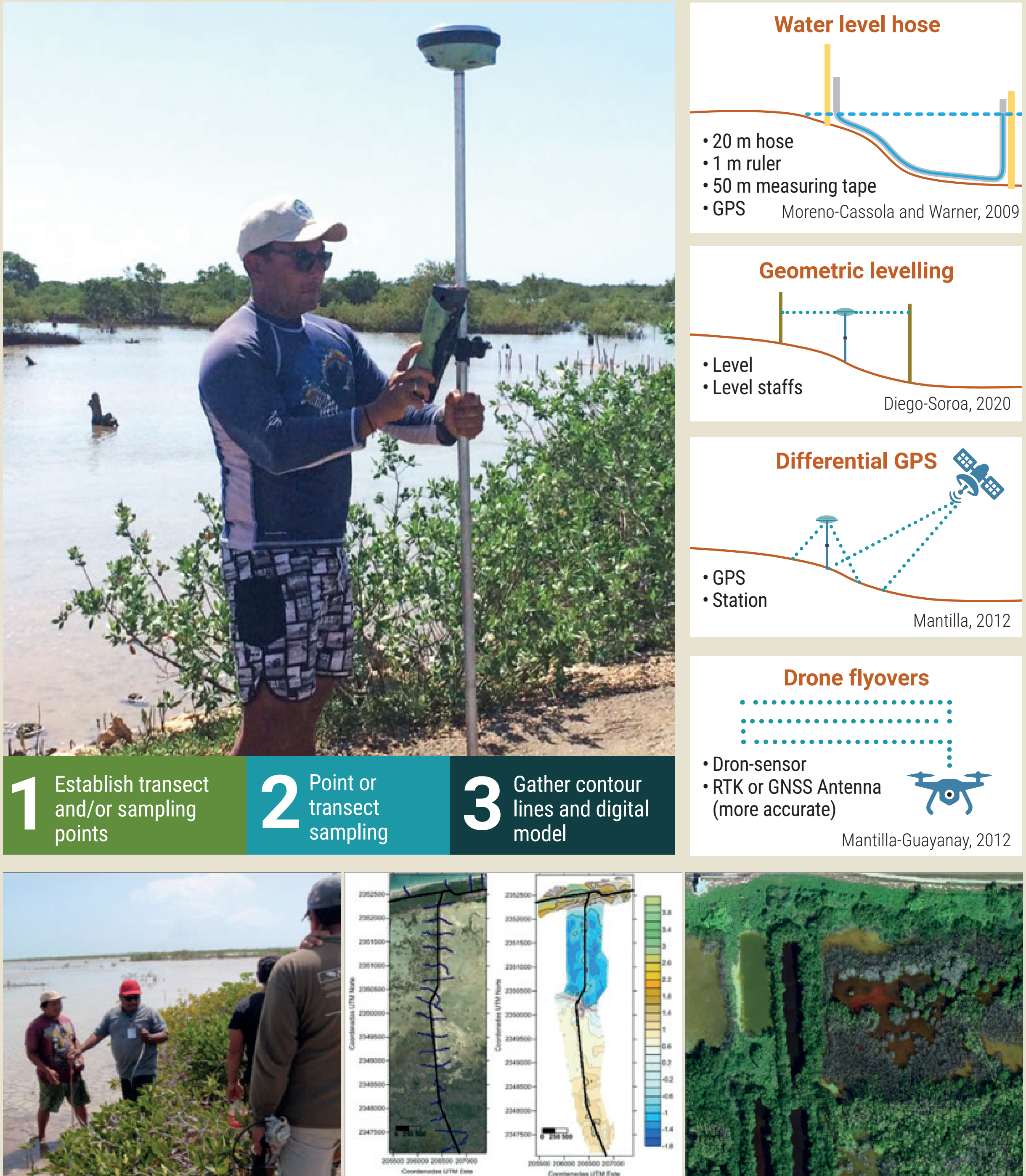
1. Topography

In a degraded mangrove, it is common to see topographic variations in respect to the reference site. The soil level may subside due to the oxidation of organic matter, or it can rise due to infill, dredging deposits, or changes in hydrology and sedimentation. Microtopographic changes in a dredged site can, in turn, lead to changes in the hydroperiod (Text box 2.3). Measurements taken during the forensic ecology can help identify runoff sites and zones with greater/lower topographic levels (Fig. 2.8). It is also possible to identify zones that need to be modified by elevating or reducing the topography and the best locations to build canals, if necessary.

It is recommended to conduct a bathymetric analysis of the site and the neighboring bodies of water that influence the mangrove. This will help create hydrodynamic models in order to identify the permanently or temporarily flooded zones and preferable flows, thus determine the restoration actions most suitable for the specific topography of the site and maximize the restoration success (Twilley and Monroy, 2005; Pérez-Ceballos *et al*., 2017).

TEXT BOX 2.3

The topography is one of the key controllers of the hydroperiod which, in turn, regulates the occurrence of salinity gradients, oxygen availability, and the associated ecological processes (productivity and biogeochemical cycles in the water column and sediment) (Twilley and Rivera-Monroy, 2005; Alongi, 2009; Reddy *et al*., 2013).



Measuring of typographic level using the hose technique.

Typographic model of transect measurements.

Orthomosaic generated using photogrammetric images captured with a drone camera.

Figure 2.8 — Methodological alternatives for measuring microtopography during the characterization of mangrove sites. Prepared by Oscar Pérez, Andrés Canul, and Diana J. Cisneros.

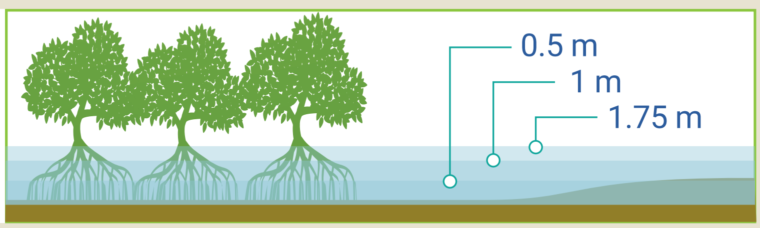
2. Hydrology

Changes in hydrology are generally the leading causes of mangrove degradation (Text box 2.4). The water sources that influence the wetland and its hydroperiod (Fig. 9), which is the flooding level, time, and frequency, must be considered (Mitsch and Gosselink, 2007). In a degraded site it is common to see that flooding patterns have been altered. If the site remains flooded for an extended period, soil oxygenation will not be possible; conversely, if water is absent, sediment hypersalinity may occur. Or if flooding levels rise beyond the physiological tolerance of mangrove species, it can cause death.

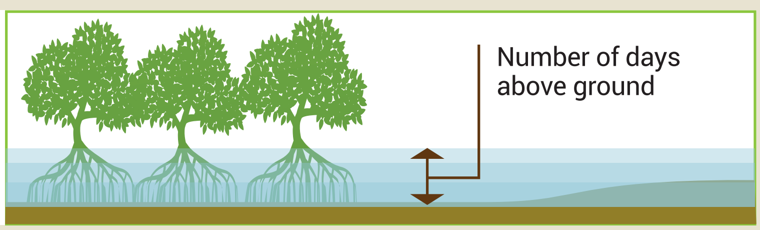
It is also necessary to determine if there was a disconnection of the natural water flows within the mangrove system. Tools such as Google Maps and the collaboration of indigenous peoples, local communities, and traditional communities who hold a broad knowledge of the site can be useful in identifying areas where hydrological patterns have been altered.

TEXT BOX 2.4 — THE HYDROPERIOD IS COMPOSED OF:

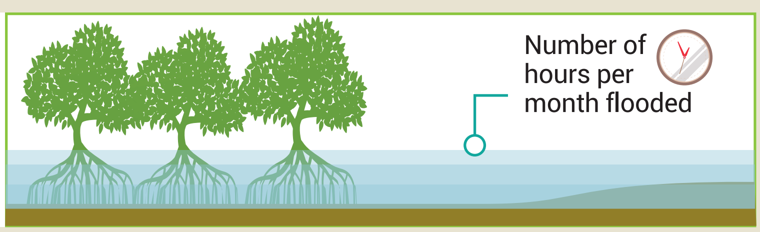
1) Flooding level: the height of the water column above soil level (m; monthly average).



2) Flooding frequency: it refers to the number of days per month in which a water column is above soil level.



3) Flooding time: it is the sum of hours in which the mangrove soil remains flooded every month.



The hydroperiod regulates several ecological processes in the mangrove at different spatial and time scales. It regulates biogeochemical processes of sediment, as well as physicochemical variables of water, such as salinity and oxygen availability. It also regulates the presence and distribution of species given their differential tolerance to flooding. Changes in hydrology may result in the death of mangrove and a limitation for propagules to establish naturally (Twilley and Rivera-Monroy, 2005).

1 Selection of sites with greater/ lower level

2 Point or continued measurements

Automatic pressure sensors

- Automatic pressure sensor
- PVC pipes (polyvinyl chloride)

Moreno-Cassola and Warner, 2009

Piezometer

- PVC pipes
- Probe to measure depth
- Flexometer or wood ruler

Diego-Soroa, 2020

Level staff

- Level staff
- Flexometer or wood ruler

Diego-Soroa, 2020

Automatic pressure sensor of the HOBO brand

Placing automatic pressure sensor at preserved reference site

Figure 2.9 — Measurement of hydroperiod in degraded site and reference site using different tools and techniques. Prepared by Oscar Pérez, Andrés Canul, and Diana J. Cisneros.

3. Physicochemical properties

Measuring physicochemical properties at the good and bad reference sites and at the site to be restored will determine which variables have been affected, and the extent of their change (Fig. 2.10). These measurement consist of taking interstitial and superficial water samples (if any) at all sites. The recommended physicochemical variables to measure are salinity, temperature, pH, redox potential, sulfur, and inorganic nutrients (nitrites + nitrates, phosphate, ammonium). The analysis of these variables will provide an approximate estimate of the extent of degradation and recovery of the restored site (Text box 2.5).

If it is not possible to measure all physicochemical variables, then properties such as interstitial salinity, temperature, pH, and redox potential, both interstitial and superficial water (if present) are the key variables to be used for characterization and to conduct further monitoring (Fig. 2.10).

TEXT BOX 2.5

The physicochemical variables are factors that regulate the structure and function of mangrove ecosystems (Twilley and Rivera-Monroy, 2005). Among them, the salinity that falls outside the ranges of tolerance of mangrove species represents a physiological stress, limiting their growth and distribution.

Moreover, the redox potential and pH are regulated variables and/or stressors associated to the hydrology of the site. The oxidation state of the soil (redox potential), the sulfur content, and its speciation and sulfur distribution (sulfide) are factors related among them and determine the pH of the soil (Oxmann *et al*., 2010; Sha *et al*., 2018).

These variables, in turn, are related to the decomposition of organic matter and nutrient availability, like P and N, involved in the reactivation of biogeochemical cycles and regulating the establishment, survival, and growth of wetland plants and animals (Mitsch & Gosselink, 2007; Reddy & DeLaune, 2008; Oxmann *et al*., 2010).

Figure 2.10 — Techniques to measure physicochemical variables of interstitial and superficial water (*if present) for mangrove characterization and monitoring. Prepared by Oscar Pérez, Andrés Canul, and Diana J. Cisneros.

4. Soil

The soil in mangrove ecosystems is the largest organic carbon storage, hence a key component. In a mangrove in good condition, the content of organic matter stored in the soil is a good conservation indicator. In degraded zones, the changes in the hydroperiod cause oxygenation and a fast decomposition of organic matter, so the content of organic matter, and therefore carbon, tends to be lower (Text box 2.6). The variables to measure sediment properties are the content of organic matter, bulk density, and carbon-nitrogen-phosphorus ratios (Fig. 2.11). These variables serve as indicators of the soil condition. They can reveal any impacts that have occurred and the nutrient content available in the sediment. It is also possible to determine if the soil is fit for plant growth. Although rapid changes occur in the first 30 cm of the soil, which is the most vulnerable layer, deeper layers can also be affected in wetlands (Hooijer *et al*., 2006).

TEXT BOX 2.6

Changes in the hydrology of the site can be reflected on the characteristics of soil, so they serve as integrating variables to learn about the impacts and bigeochemical processes that have occurred through time. Soil characteristics show the impact on the nutrient and pollutant load of the site (Rodríguez-Zúñiga *et al*., 2018). Given that physical indicators of soil can remain further in time in which soil conditions have been altered, these indicators are considered permanent and stable, and so they have a strong value when assessing the site (Campos and Moreno-Casasola, 2009; Rodríguez-Zúñiga *et al*., 2018).

Figure 2.11 — Techniques and variables for characterizing mangrove sediment. Prepared by Oscar Pérez, Andrés Canul and Diana J. Cisneros.

For soil analysis, it is necessary to collect cores (Fig 2.11), and the number required will depend on the established sampling points, both at the reference site (preserved/degraded) and the restored site. This will allow for comparisons to be made between sites, in addition to the recovery at the restored site. When collecting cores, a color description must be systematized using Munsell charts, as well as the thickness of the different soil layers and the presence of visible organic matter, which can be used as "proxy" variables if lab analysis is not possible (Fig. 2.12).

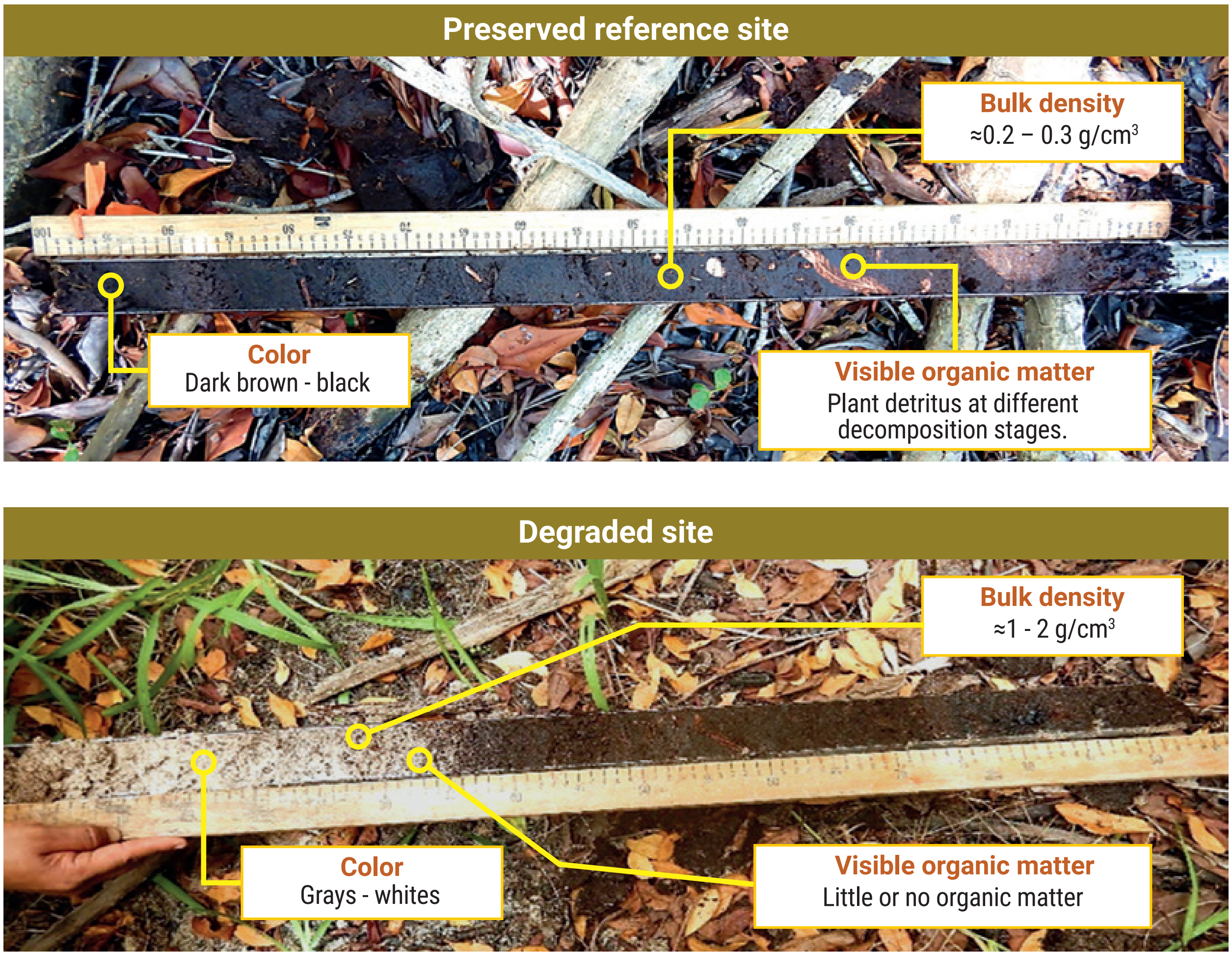


Figure 2.12 — Comparison of proxy variables, such as color, bulk density, and visible organic matter in sediment cores of one preserved reference site and one degraded reference site.

5. Vegetation

The assessment of forest structure within the degraded and reference sites provides an approximation of the conditions in which the site was found prior to being disturbed (Text box 2.7). The proximity of a site in good condition can function as a source of mangrove propagules and seeds to naturally regenerate the site.

The degraded site can present patches of vegetation or dead trees at different levels of decomposition. Measuring the remaining vegetation within the site will determine the previous structure and composition of the site.

The following variables are recommended for measurement: total height, normal diameter or diameter at breast height (ND or DBH), basal area, the density of individuals, number and frequency of species, Importance Value Index (IVI), and repopulation potential (quantification of seedlings and juveniles) (Fig. 2.13). Once specific variables are chosen during the forensic ecology, they should be measured throughout the monitoring process of the restoration, carefully following the same techniques and using the same equipment to minimize sampling errors.

TEXT BOX 2.7

The mangrove structural variables are indicators of the ecosystem condition. The structural characteristics are a proxy of the restoration outcome and are based on the physiognomy type of mangroves where the intervention is taking place (fringe, watershed, dwarf, etc.).

The measurement of the repopulation in the reference site helps to establish the population dynamics and check if the forest is able to produce enough propagules and seeds to establish new individuals. Once the hydrology of the site is restored, these can be disseminated to the area under restoration and, if the suitable conditions have been recovered, they can establish and grow. The species composition of the preserved site provides information about the species that are expected to regenerate naturally on the site, or those that can be used for reforestation purposes, if necessary.

Figure 2.13 — Measurement of vegetation structure and composition in reference and degraded sites. Due to a high environmental and structural mangrove heterogeneity, general guidelines have been developed for measuring mangroves, which can be consulted in Cintrón and Schaeffer-Novelli (1983), Kauffman *et al.*, (2013), and Rodríguez-Zúñiga *et al.*, (2018). Prepared by Oscar Pérez, Andrés Canul, and Diana J. Cisneros.

4 Restoration actions

Ecological restoration actions aim to recover the environmental, hydrological, and physicochemical conditions that enable the establishment and growth of vegetation (Text box 2.8). The designed strategy for implementing restoration actions must be based on the forensic ecology outcomes (Step 3), where a site-specific action plan is determined according to the topographic, hydrological, physicochemical, and biological characteristics of the site (Fig. 2.14).

The action plan must include monitoring the restoration to assess if the implemented actions are working, or if changes must be implemented through an adaptive management apporach, all based on the goals and objectives set out by the working group (see chapter 2.5). Moreover, it must also include workshops and capacity-building for the community. The action plan should also include the established goals and objectives and the time planned to achieve them.

TEXT BOX 2.8 — ECOLOGICAL RESTORATION ACTIONS

The main objective is to recover the environmental conditions that favor the establishment and growth of mangrove, in order to recover the structure and function of the ecosystem.

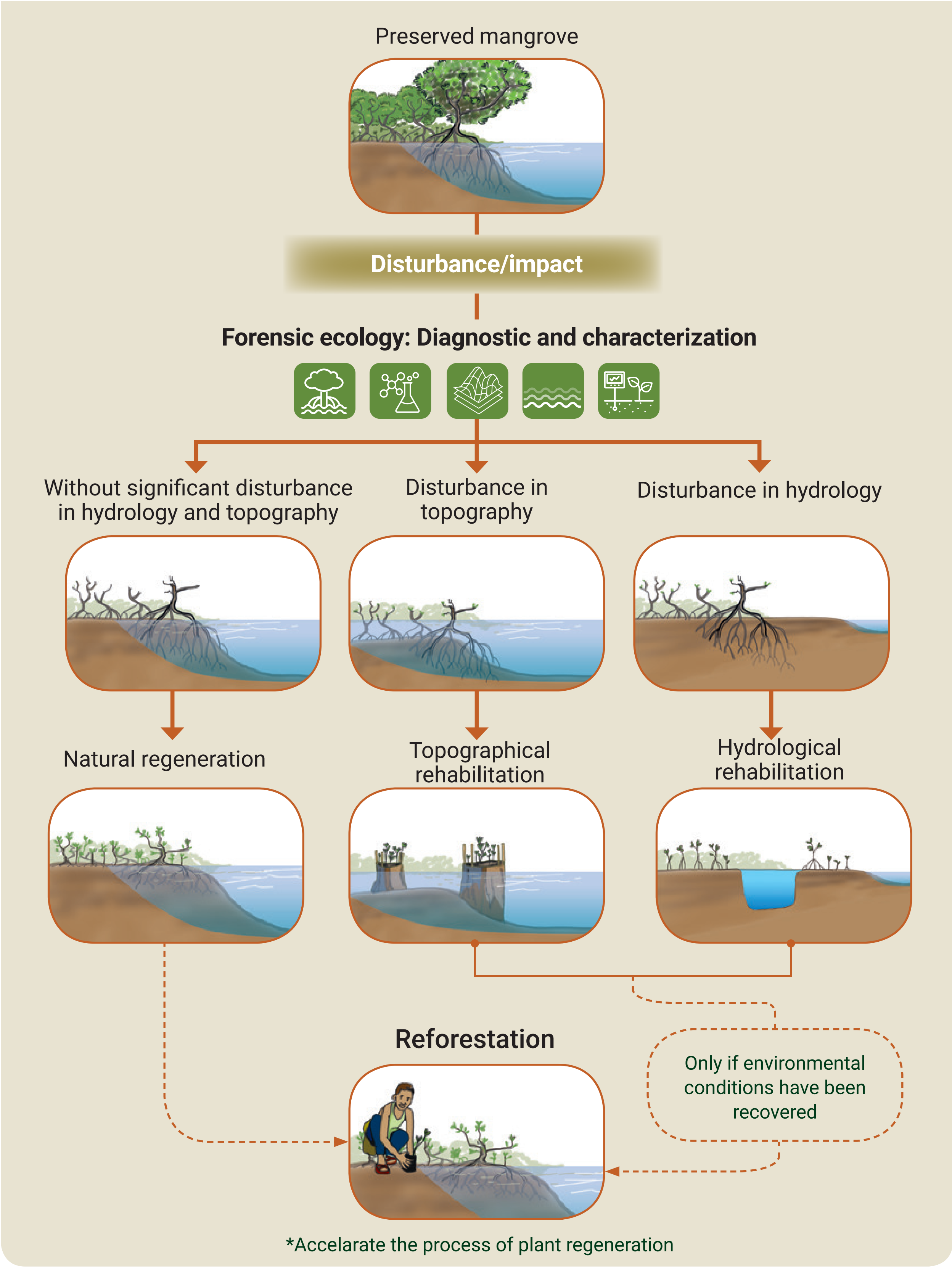


Figure 2.14 — Decision flowchart for developing an action plan and selecting the restoration actions to be implemented. Prepared by Diana J. Cisneros.

Action plans can be divided into two types: passive (hydrology restoration) and active (topography rehabilitation and/or reforestation) (Fig. 2.15). It is recommended that restoration actions are implemented in collaboration with different sectors, involving community members, civil society organizations, local businesses, academics, and government entities. During the implementation of the restoration, it is important to keep record of activities and actions to track progress, and a photographic record must be kept.

Hydrological Rehabilitation

Objective: Restore the hydrology by reconnecting water flows with freshwater and/or marine brackish sources in the degraded zone, in order to restore the flooding level, duration, and frequency that enables the restoration of physicochemical conditions of water and soil.

- Desilting of natural canals
- Creating new canals
- Desilting of waterways

Topography Rehabilitation

Objective: Modify the field level in order to restore adequate flooding patterns and levels for the establishment and growth of plants.

- Sediment removal (lowering topography)
- Dispersal centers (raising topography)

Reforestation

Objective: Accelerate the recovery of mangrove structure and function. It should be implemented only if the environmental conditions are suitable for the establishment and survival of seedlings.

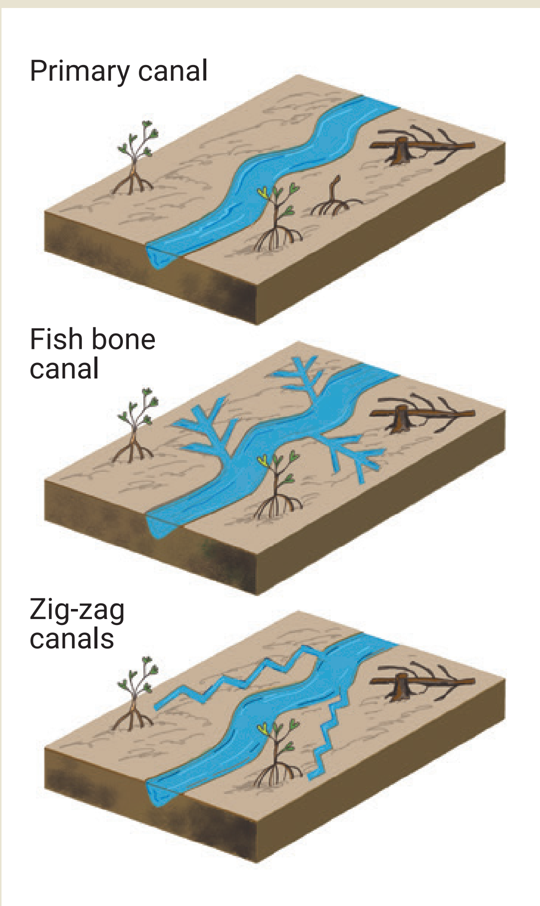
- Direct planting
- Nursery

Figure 2.15 — The key types of actions for mangrove ecological restoration. Prepared by Oscar Pérez.

1. Hydrological rehabilitation

Hydrological rehabilitation (passive rehabilitation) can be implemented with actions, such as desilting waterways and natural canals, or the creation of new canals. The location of canals will be defined from the information collected during the forensic ecology steps to identify areas where waterflows have been interrupted, the course of natural flows, and the possible need to establish new canals (Text box 2.9). The participation of indigenous peoples, local communities, and traditional communities is critical during the planning of hydrological rehabilitation because they contribute with their empirical knowledge in identifying natural canals and provide feedback on preferential flow models created with the topobathymetry of the site.

TEXT BOX 2.9



Creating canals is one of the most common practices for hydrological rehabilitation. Once the hydrology of the site has been restored, adequate conditions are slowly recovered, enabling the natural establishment of seedlings.

Desilting of canals

The desilting of canals consists of removing sediment deposits or organic and inorganic solid matter which are blocking the flow of waterways, in order to achieve greater drainage capacity and optimize water circulation within the site, in accordance with the natural flow. Desilting is considered part of the maintenance that new canals require, and is recommended to be conducted every one to five years (depending on the degree of silt), preferably during the dry season. However, the design of canals may help reduce maintenance efforts. Commonly, this action suceeds in restoring the hydrology of the site and with that the condition required to trigger secondary succession, the reestablishment of vegetation (Text box 2.10).

It is important to mention that organic matter that has been removed from the site must be left within the area of the project so that it may continue with the decay process and contribute to carbon sinks. The desilting of canals must be implemented with the participation of technical or specialized staff and the community (Fig. 2.16).

TEXT BOX 2.10

It is recommended that the width and depth of canals resemble the natural configuration of each site in order to be heterogeneous and that the ebb and flow of water does not easily erode the side slopes of canals; therefore, maintenance actions will be needed less often (Teutli-Hernández *et al*., 2020). Sediment should not be left on the edges of the canal. This is not a good practice because it obstructs the flooding towards degraded zones on both sides of the canal.

Figure 2.16 — Steps and recommendations for the desilting of natural canals as a restoration action. Prepared by Oscar Pérez, Andrés Canul and Diana J. Cisneros.

Rehabilitation of culverts

Building roads is one of the most common causes of adverse changes in the hydrology of a site (Teutli-Hernández and Herrera-Silveira, 2018). During the construction of roads, the general culvert design is ineffective because it does not allow the adequate exchange of water between both sides of the road (Text box 2.11). In this case, it is necessary to rehabilitate the existing connecting canals (Fig. 2.17).

It is suggested that culverts have an inverted "Y" shape from the connection point of the culvert, with an approximate length of 5 m, having a connection point with canals (Fig. 2.17). This action aims to broaden the spatial distribution and range of the water passing through these structures as much as possible. The canal depth must be at least 1 m to ensure the water flow between each side of the culvert, even during low tides and lowest water levels. These guiding measurements must be adjusted based on the water flow intensity, the depth of the bedrock, and the area to be restored.

TEXT BOX 2.11

Culverts need to be properly built to allow water to flow between both sides. The desilting strategy and the proper modification increase the probability of water flowing in different directions towards the wetland to be restored and reduce the risk of blocking. Therefore, maintenance actions will be less frequent (1 to 5 years).

Culvert blocked with debris

Desilted culvert with an inverted "Y" shape

Recommendations

A depth of at least 1 m should be considered to ensure that the water flows between each side, even during low tides and dry season.

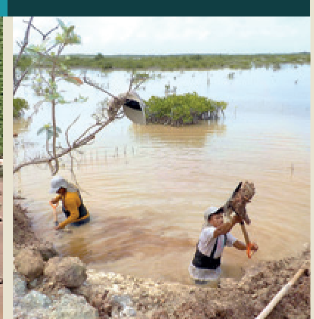
1 Identify blocked culverts

- Google Earth ©
- Computer equipment

2 Design inverted Y-shaped canals

- PVC piping

3 Removed sediment buildup



- Shovels, picks and wheelbarrows
- Backhoe

Figure 2.17 — Culvert rehabilitation to restore water flow in affected sites due to road constructions. Prepared by Oscar Pérez, Andrés Canul and Diana J. Cisneros.

Creating new canals

Creating new canals must be considered when the desilting of natural canals is not enough to restore the hydrology of a site. The objective of creating new canals is to ensure continuous water flow with inlets and outlets. The canal network is established using information collected from forensic ecology. The building of canals requires hand tools or, if necessary, heavy machinery, such as excavators, but it will depend on the characteristics of the site and the size and resources of the project (Fig. 2.18).

Specifications of new canals regarding depth and width will vary depending on the unique conditions of sites, and should attemp to resemble the natural configuration of canals (Text box 2.12). An inclination of 30-45º is recommended for canal slopes and must be at least 1 m in depth (based on the characteristics of the site, in shallow soils may be down to 0.5 m), in order to provide heterogeneity and that the ebb and flow of water will not erode the slopes of the canals, reducing the frequency of maintenance. The sediment removed is commonly left on canal banks, which prevents the influence of the canal from spreading beyond its edges. It is recommended to spread the sediment, or have it used for other complementary actions, such as filling sites with a lower topographic level (see section on sediment removal in chapter 2.4.2).

TEXT BOX 2.12

When communities are engaged in restoration actions, it allows them to take ownership of the value of the site. Training them is essential, as well as providing all the necessary supplies so that actions are carried out under required security measures.

Figure 2.18 —Steps and recommendations to building new canals that enable degraded sites to restore their hydrology. Prepared by Oscar Pérez, Andrés Canul and Diana J. Cisneros.

2. Topography rehabilitation

This action takes place when the topography of the area to be restored presents changes compared to the reference site in good condition (Text box 2.13). The topographical changes in the degraded site impact the hydrology of the site, eroding the sediment or altering flooding levels and frequency. Therefore, it does not enable the establishment of mangroves, which is when sediment must be removed. There can also be permanently flooded areas (> 1 m) due to the sinking of sediment as a result of decayed organic material, thus increasing the flooding level and preventing mangrove seedlings or seeds from establishing, in which case the topography needs to be elevated.

TEXT BOX 2.13

An heterogeneous ecosystem will favor the replenishment with different species, giving way to a secondary succession process and providing better chances of withstanding or recovering from an impact, as compared to a homogenous system, such as monospecific reforestation.

Sediment removal

This action consists of lowering the topography level of higher grounds. It can also take place as part of the maintenance of culverts, desilting of natural canals, or from the creation of new canals (see chapter 2.4.1). For sediment removal, it is important to identify areas of higher topography levels, this is done through topography modeling in combination with hydrology models. This information will help determine the locations where the sediment can be removed (Fig. 2.19). Raking the sediment helps to level canal banks and remove salt crusts that may have formed, promoting the natural regeneration of the site.

Figure 2.19 — Steps and recommendations for sediment removal for the topography rehabilitation in the mangrove ecological restoration. Prepared by Oscar Pérez, Andrés Canul and Diana J. Cisneros.

Dispersal centers

In cases where topography levels are lower than those of the good reference site and flooding levels are too high and do not allow seedlings to establish, dispersal centers (DC) can be used. The DC, also known as silt platforms, are modifications of the topography that raise the topography level and create the conditions to allow for seedlings to establish (Text box 2.14). Preliminary studies on the use of DCs report that they create adequate physicochemical conditions of sediment for the establishment of mangrove seedlings (Pinzón-Vanegas, 2017).

TEXT BOX 2.14

Dispersal centers are topographic modifications that raise the level so that flooding conditions are adequate for seedlings to establish. These dispersal centers must be built with at different levels in order to have topographic heterogeneity that will foster greater diversity and resilience in the ecosystem.

Dispersal centers can be built in different ways using different materials depending on resource availability for each project or region. The material from which they are built must be permeable, allowing water to flow yet avoiding sediment from washing out. Examples of this material are geotextile mesh or shade mesh. It is recommended that DCs are handmade with the help of community groups involved in the project. The mesh is propped with at least four wooden poles of approximately 1.5 to 2 m in length, tied with marine tarred twine. Plant material can also be used, for example, branches or any material that can hold the sediment and maintain an adequate elevation. The height of DCs must be equal to or lower than 5-10% of the maximum flooding height of the site to be restored (this is measured based on the level of the reference site in good condition), for which the diagnostic data is critical to define these details accurately. It is recommended that the final height of DCs is similar to the reference site in good condition (Fig. 2.20).

The sediment used in DCs is obtained from the desilting process or the building of canals (Fig. 2.20). However, it is important to ensure good drainage in DCs, for which sediments with high silt and/or clay content should be mixed with 20-30% sand. These features make DCs more stable for their height, and therefore allow for the correct flow of water and salinity conditions for seedlings to establish. The mesh structure with poles can be recycled later when individuals are recorded to be structurally established.

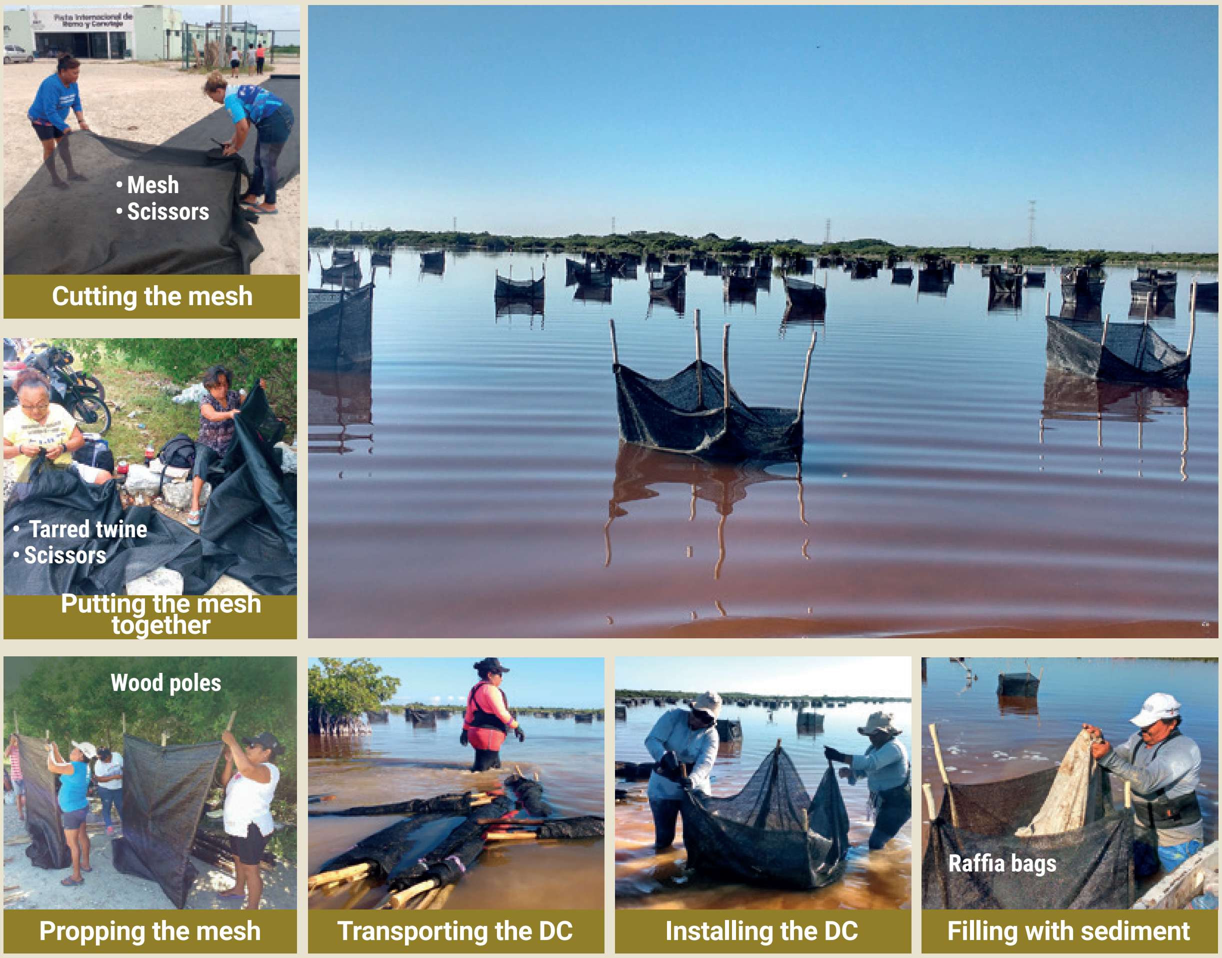


Figure 2.20 —Building dispersal centers for topography rehabilitation. Prepared by Oscar Pérez, Andrés Canul and Diana J. Cisneros.

Regarding distribution, it is suggested to form random clusters consisting of 5 dispersal centers covering a determined area (Fig. 2.21). The number and location of dispersal centers should be decided based on the range and initial conditions of the site to be restored, considering the topography and preferential flows, as well as the availability of financial resources. The DC area can vary, but a diameter of 1 to 5 m has proven the most efficient in restoring vegetation.

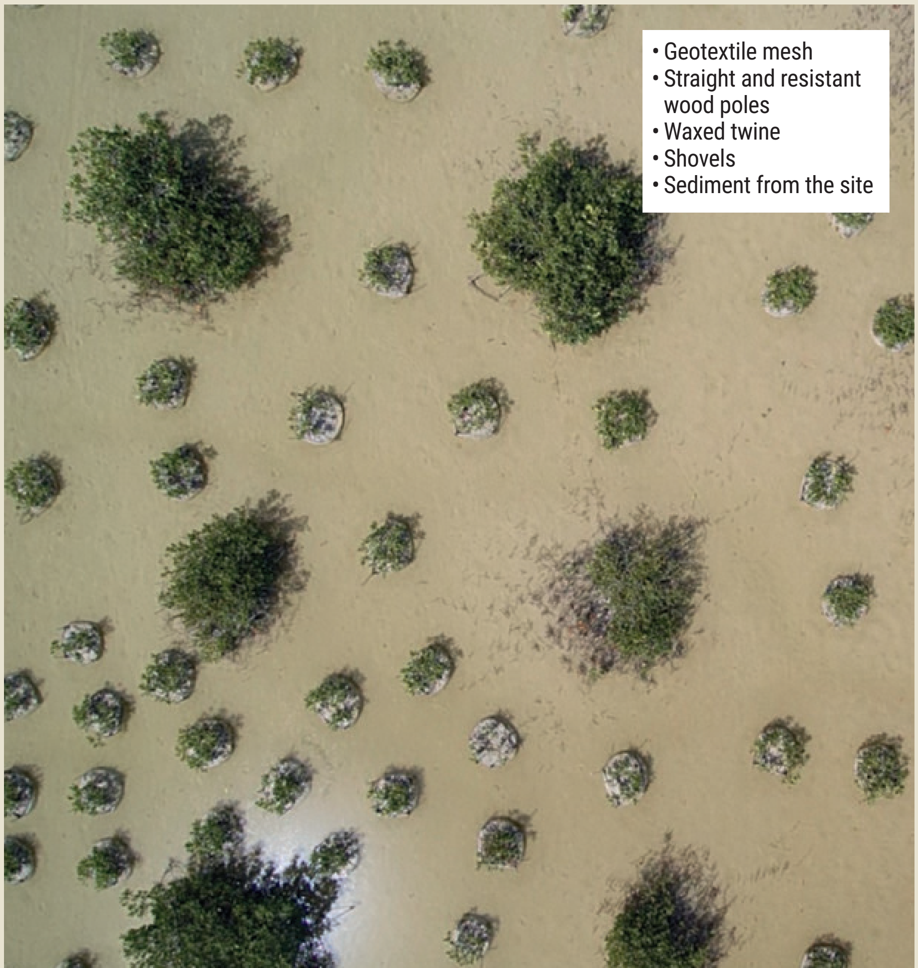
Dispersal centers (raised topography)

Selection of DC location

Putting together the DC with shade mesh

Installing DCs in flooded areas

Clusters formed with 5 dispersal centers



1 Selecting the location

2 Putting it together

3 Installation

It is suggested to locate them in sites where the flooding level is greater than 0.4 – 0.5 m asl and an interstitial salinity of < 80 PSU.

They can be zones of natural establishment or reforestation, which will help accelerate the recovery process through an active restoration.

Figure 2.21 — Installation of dispersal centers in mangrove degraded areas. Prepared by Oscar Pérez, Andrés Canul and Diana J. Cisneros.

3. Reforestation

Reforestation has been the most used technique globally for mangrove restoration projects (FAO, 1994; Teutli-Hernández, 2017). However, if this action is carried out without a proper analysis of the environmental conditions in which the site is found, it can result in a waste of resources and effort and an unsuccessful endeavor. Reforestation is recommended if seed and propagule dispersal is not sufficient in the site due to a low natural regeneration rate. Reforestation accelerates the recovery of mangrove structures and functions and strengthens community participation at the site (Text box 2.15) (Teutli-Hernández, 2017; Brown *et al*., 2014).

When reforestation is chosen as an action to take, the site to be restored must have the proper environmental conditions (hydrological and physicochemical) for the establishment of seedlings. If conditions are not suitable, the corresponding restoration actions must be carried out before planting, and seedlings must be previously acclimated to the salinity and light exposure of the location.

TEXT BOX 2.15

The reforestation to be implemented must foster the environmental heterogeneity, which provides a higher resilience to the system, avoiding monoculture plantations that do not ensure the system to recover its ecological functions. Reforestation species must be selected based on those recorded in the preserved or reference site.

Direct planting

Direct reforestation consists of planting propagules, allowing seedlings to develop functional strategies suitable for the environmental conditions in which they are found (Cisneros-de la Cruz, 2019). As a result, seedlings can have a higher survival rate and build resilience. It is recommended that the seedlings used in restoration comes from preserved areas close to the site (it can be the reference site in good condition) and must consider its composition for species selection.

It is also important to collect propagules from different trees, preferably separated by at least 10 meters from each other, which promotes genetic diversity of propagules to be planted. Plant material collection is carried out with the participation of communities trained to distinguish if seeds or propagules are healthy, mature, and disease-free (Fig. 2.22). It is important to consider the appropriate government permits required for collection, as there may be regulations that protect and manage mangrove species in the region.

Figure 2.22 — Reforestation by planting mangrove seeds or propagules. Prepared by Oscar Pérez, Andrés Canul and Diana J. Cisneros.

Nurseries

Nurseries are useful to speed up the growth process of mangroves when the natural regeneration rate of mangrove forests is low (Lewis III, 2005). Nurseries allow the control of propagule growth until seedlings are less vulnerable to herbivores, flood levels, and tidal force (Melana *et al*., 2000; Ravishankar and Ramasubramanin, 2004). The planted propagules must come from sites close to the area to be restored, allowing plants to have a greater adaptation capacity (Proffit and Travis., 2010).

In addition, species found in the reference site must be planted in the restoration site to produce a more diverse and resilient mangrove. When establishing a nursery, it is necessary to consider the environmental conditions in which propagules will be transplanted. If seedlings are grown under low salinity and solar exposure and are planted under contrasting conditions, they will be subjected to physiological stress that will cause them to die. Therefore, cultivating them under conditions similar to the site or with proper acclimation is critical to increasing the chances of seedling survival. To that end, it is necessary to understand and consider the physiological limits of the species (Text box 2.16).

TEXT BOX 2.16

Plant material is collected with the participation of communities, who are trained to distinguish if seeds or propagules are in optimal state to plant them. It is important to understand the fruiting season and phenology of each species. Species selection must be carried out based on the salinity of the degraded area or area of interest. Preferably, the nursery should undergo periodical flooding and have access to fresh and salt water.

Reforestation is an activity that strengthens the social engagement of different types of stakeholders and encourages them to take ownership of the ecosystem. However, it must always be done considering the species autecology and when the environmental conditions have been restored.

San Martín, Mullet Bay, Nature foundation, 2019.

5 Monitoring

Monitoring allows for the restoration progress to be evaluated in terms of the objectives and specific goals set for the project. It is important to consider the follow-up of the restoration, as far as possible, for at least five years, to make adjustments under an adaptive management approach, to achieve the planned objectives and goals (Biswas *et al*., 2009). Monitoring involves evaluating success criteria through a systematic follow-up and analysis of indicators (Fig. 2.23).

Indicators are specific and quantitative attributes which assess objectives over short-, medium- and long-term timeframes. In order to assess the progress in restoration, it is necessary to measure indicators at reference sites in good and degraded conditions, and at the restored site, to show the extent of recovery of the restored site, what needs to be achieved regarding the goals set and what has been improved regarding the initial degraded state (SER, 2004; Marchand *et al*. 2021).

There are critical indicators that should always be measured because they are key variables in mangrove ecosystems. In contrast, other indicators are complementary or with a higher specificity according to the unique goals and resources for each project. The number of indicators and the sampling frequency are determined by the objectives and human and financial resources available. The establishment of community monitoring systems is recommended; this is where society is involved in the evaluation process. This allows communities to take ownership of the ecosystem, thus building citizen oversight.

In any of the cases, it is essential that monitoring is incoporated into an adaptive management approach, which makes it possible to deal with the uncertainty and the complexity of the ecosystem, and, if necessary, to adjust strategies for improving results based on the data generated by the monitoring program (Biswas *et al*., 2009).

Ecological indicators consist mainly of variables that were used and their methodologies described in the forensic ecology section, which allows for a follow-up to be carried out during the restoration (see section 2.3), in addition to other variables that assess the recovery of the site's biodiversity. Moreover, the socioeconomic component must also be assessed to be able to evaluate the cost-benefit aspect of restoration and strengthen restoration practices. At the same time, it ensures social engagement and well-being and the continuity of outcomes by sustainably harnessing resources.

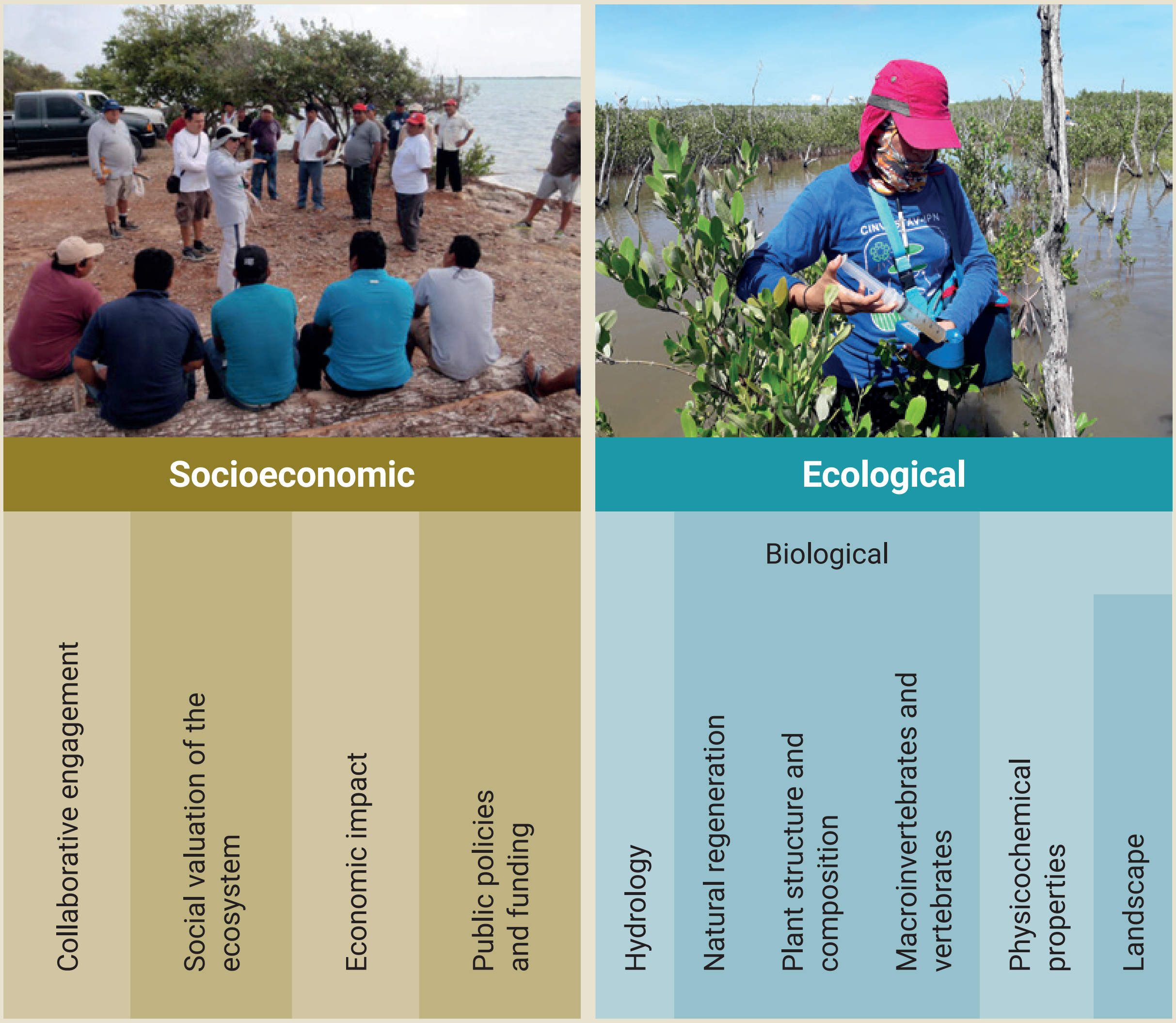


Figure 2.23 — Evaluation criteria to consider during the monitoring of ecological restoration of mangroves.

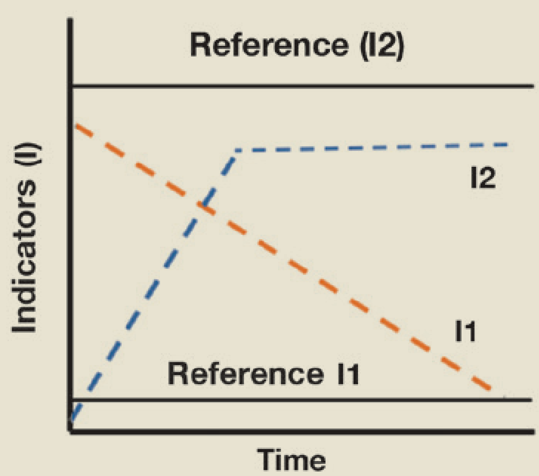
Ecological and socioeconomic criteria are described below, as well as indicators recommended for assessment and their involvement during the ecological restoration of mangroves.

1. Ecological indicators

Ecological indicators must reflect the environmental conditions of the restored site, for which patterns must be shown at different scales and inform appropriate actions. These indicators come from measuring the current state of the restored system. They include the mangrove structure and composition, physicochemical properties of water and sediment, and fauna assessment after restoration actions (Table 2.2). It must be taken into consideration that the primary purpose of an indicator is to measure the response of the restored ecosystem (Niemi and McDonald, 2004).

For the assessment, it is important to consider that the restoration is subject to the level of biological organization and structural and functional characteristics at different temporal and spatial scales (Suding and Gross, 2006), since processes respond differently, which makes it possible to better understand the mangrove recovery process (Allen and Hoekstra, 1987). During the assessment of attributes in a restored site, it is necessary to compare against the values found in reference sites to estimate the level of restoration success (Ruíz-Jaen and Aide, 2005), where reference sites may be well preserved or degraded. One way to conduct a quantitative evaluation of restoration projects is by repeatedly measuring indicators through time and their graphical representation in performance curves (Kentula *et al*., 1992), restoration trajectories (Hobbs and Norton, 1996), or functional equivalency trajectories (Simenstad and Thom, 1996). This refers to monitoring indicators by measuring a restored site, and simultaneously measuring a reference site, which helps to understand when and why a technique is successful and reduce the chances of failure (Fig. 2.24).

Although non-repeated measurements of structural or functional attributes may provide an excellent assessment of the success of a restoration (Smokorowski and Randall, 2017).



Adaptive management is aimed at achieving goals which reduces the uncertainty by including obtained knowledge while monitoring success indicators.

Figure 2.24 —Example of the representation of monitoring of indicators for success with performance curves in ecological restoration. Black lines represent indicators of the reference site in good condition (I1, I2), while dotted lines represent the same indicators of the restoration site and its different trajectories of change until it reaches similar values of the reference site at different velocities.

TABLE 2.2 — Ecological criteria and recommended indicators

Ecological criteria and recommended indicators for measurement during monitoring of the mangrove ecological restoration and the approximate response term expected to see significant changes. Response terms: short (days to months), medium (1-5 years), and long (> 5 years).

Criteria	Indicators	Response terms
Hydrology		
Hidroperiod	Flooding frequency	Short
	Flooding level	
	Flooding time	
Biological		
Plant structure and composition	Height, density, diameter, basal area, importance value index (IVI), plant cover, abundance, density, diversity, diversity indexes, richness	Long
Regeneration	Recruitment, survival rate, composition	Medium
Macroinvertebrates and vertebrates	Presence/absence of functional groups (fish, birds, mollusks):	Short-Long
	Abundance, density, diversity, richness	Short-Long
Physicochemical variables		
	Interstitial and superficial salinity	Medium
	pH	
	Redox potential	
	Temperature	
	Sulfide (H2S)	
	Nutrients (NH_4^+, NO_2^-, NO_3^-, PO_4^{3-})	Medium Long
Sediment		
	Organic matter in soil, bulk density	Long
	Thickness of soil layers, texture, and color of sediment	
Landscape analysis		
	Plant cover, fragmentation	Long
	Flow of organic matter and nutrients	

Success can be measured using indicators over the short- (days-weeks-months), medium- (1-5 years), and long-term (> 5 years). The monitoring frequency is given according to spatial and temporal scales during which the ecological processes occur, but they can be adjusted according to the sampling efforts and financial resources available. Early in the restoration, in the short term, monitoring activities are more frequent to assess the response to restoration actions and make changes through adaptive management, if necessary. Therefore, it is recommended to sample every 3 to 6 months during the first year.

From the second year on, the monitoring can be carried out every six months. After the third year, sampling can be done every year, once distribution patterns have begun to develop in plant growth (Fig. 2.25). However, these periods will have to adapt according to the unique conditions for each project.

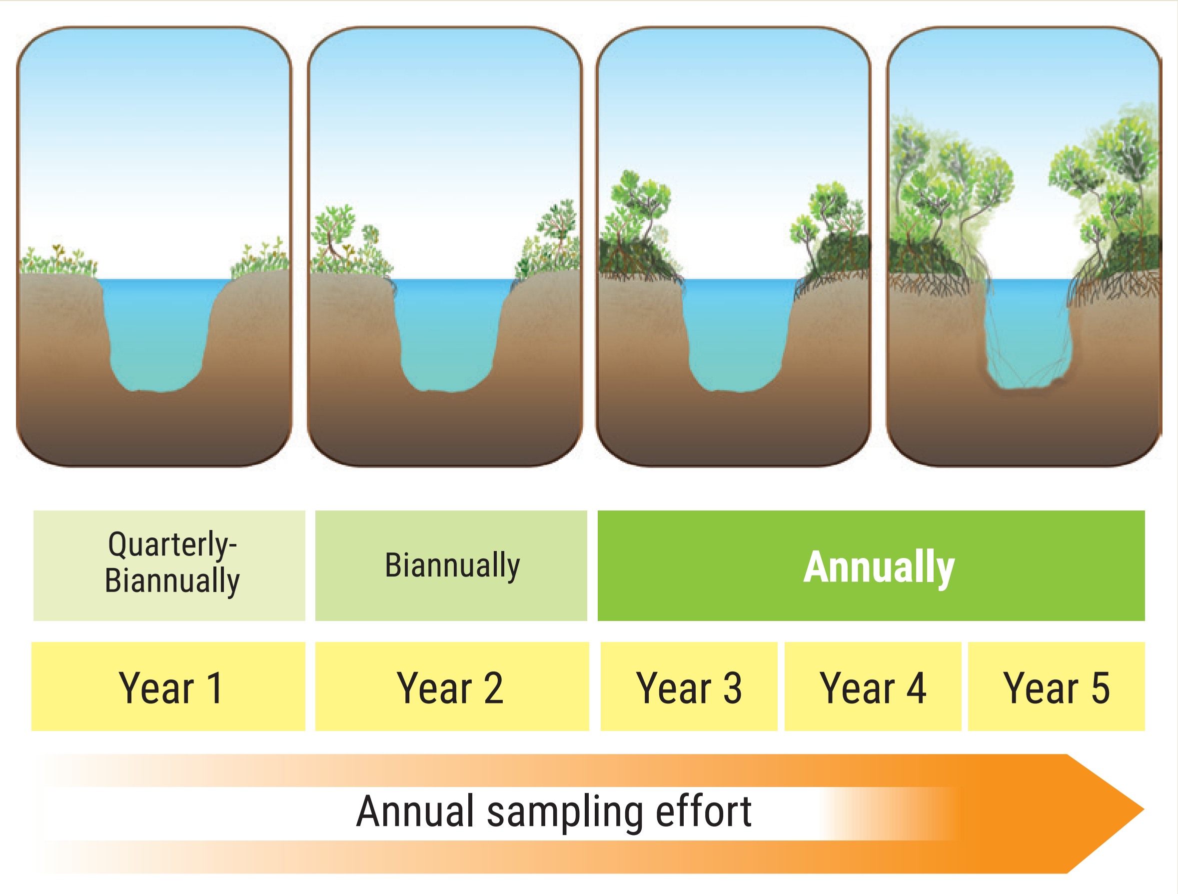


Figure 2.25 — Sampling frequencies required to monitor the process of mangrove ecological restoration. Prepared by Diana J. Cisneros.

Hydrology

After implementing restoration actions, it is expected that the hydroperiod of the restored site will synchronize with the reference site, which is one of the indicators of success during the restoration process. The recovery of the hydroperiod triggers the restoration of physicochemical conditions suitable for plant establishment and the reactivation of biogeochemical processes (Gosselink and Turner, 1978). The sensors installed during the forensic ecology will monitor the hydroperiod during the entire restoration process, recording the changes produced by restoration actions (Fig. 2.26).

Pressure sensors that measure the hydroperiod as part of the monitoring (section 2.3.2).

Figure 2.26. Monitoring of the hydroperiod during restoration.

Physicochemical variables

The variables that regulate plant growth and survival are salinity, pH, redox potential (Eh), sulfide or sulfur, nutrient concentration, among others (Twilley and Rivera-Monroy 2005), and these indicators tend to resemble those of the reference site at the medium-term (Fig. 2.27).

Salinity is an indicator that must always be measured during the mangrove ecological restoration because it is a key regulator for mangrove distribution, survival, and development (Lovelock & Feller, 2003; Rivera-Monroy *et al*., 2006; López-Hoffman *et al*., 2007), as well as plant structural development (CONABIO, 2009).

pH and temperature determine if conditions are suitable for the availability of nutrients, and provide an overview of the physicochemical process of sediment (Oxmann *et al*., 2010).

Redox potential (reduction-oxidation) is a quick measurement of the state of reduction-oxidation that estimates the stability of several compounds regulating the availability of nutrients and metals in sediments, as well as the levels of decomposition of organic matter related to the pH and free oxygen content that favors the process (Herrera-Silveira *et al*., 2013). It is associated with the reduction or oxidation properties of sediments and represents an indicator of the biogeochemical processes during the state of decomposition of organic matter.

Dissolved inorganic nutrients indicate the trophic grade, water quality, and its origin since they are indicators of processes that occur in mangrove sediments. The concentration and variations of inorganic nutrients explain the connection between physicochemical variables of sediment and hydrology (Herrera-Silveira *et al*., 2012).

Figure 2.27 – Sampling of interstitial water (A), measuring pH and redox potential with multiparametric (B), and salinity, with a refractometer (C).

Biologicals

Plant structure

Plant structure is the most used indicator because the recovery of mangrove forests is the most obvious goal in restoration. It is related to the restoration of the associated ecological functions (productivity, nutrient exchange, carbon sequestration) and can reach similar values as the reference site in periods between 10 to 15 years, and even up to 30 years (McKee and Faulkner, 2000; Donath *et al*., 2003; Bosire *et al*., 2008; Matthews *et al*., 2010). Throughout the project, seedlings grow and develop into juveniles and adults; therefore, the size of permanent plots must expand during this process (Fig. 2.28). Indicators for assessing plant structure are the same used for the characterization of plant structure, suggested by Schaeffer-Novelli and Cintrón (1990) (see chapter 2.3.5).

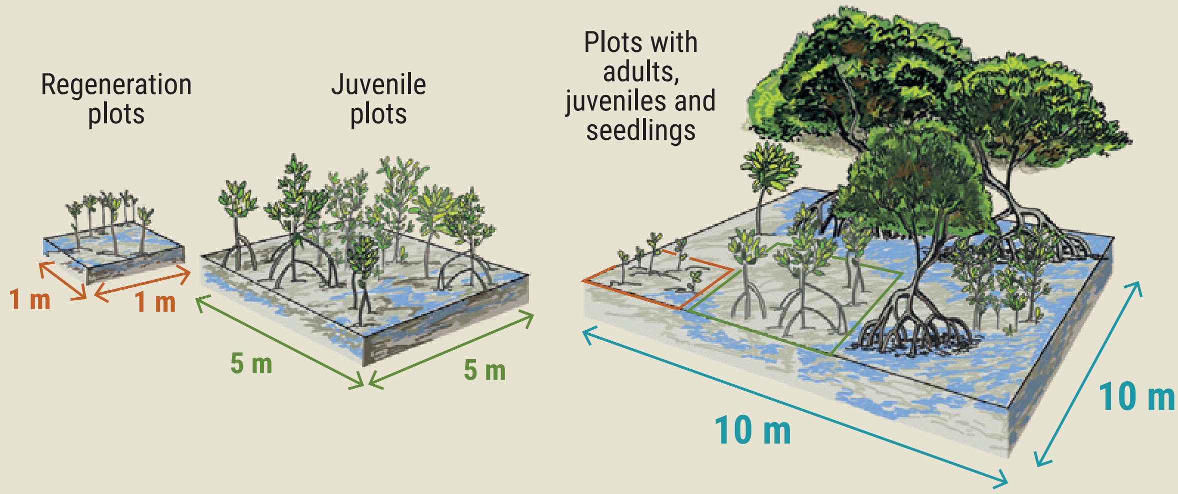


Figure 2.28 — Plot sizes for the evaluation of plant structure throughout the restoration process and plant development. Prepared by Heimi G. Us Balam.

Natural regeneration

Natural recruitment both in pioneer species (Text box 2.17) and mangrove species is a medium-term success indicator (Lewis III, 2005; Kamali and Hashim, 2011; Teutli-Hernández *et al*., 2019). The growth of pioneer species (e. g., Batis spp., Salicornia spp.) contributes, for example, to reduce the salinity, decrease the temperature of the sediment crust, increase nutrients, and retain seeds and propagules, consequently increasing the recruitment, growth, and survival rates of mangrove species (Teutli-Hernández *et al*., 2019).

In mangrove seedlings, the variables to measure are species, height, diameter, and density (see chapter 2.3.5). After the first year of restoration efforts, monitoring is recommended at least every six months, to track the growth and density of seedlings. The 1 m2 grid squares are used for the monitoring of seedlings, covering the area established in the characterization. It is recommended to have as many replicates as possible, with a minimum of 15 seedling plots. In order to evaluate pioneer species, the total area of the grid is assessed.

TEXT BOX 2.17

The regeneration is a biological indicator of the forest dynamics and allows assessing the natural recovery of plants in degraded areas.

Macroinvertebrates and vertebrates

The different types of biological diversity (taxonomy, function, species, genetics) is a key attribute of ecosystems, reflecting their performance and the state of health. This diversity declines due to environmental degradation and other impacts on ecosystems. The loss of species, guilds, functional groups, prey in the food chain, etc., can reveal a scenario containing the most resistant organisms because they adapt better to these changes, and eventually they become the dominant species of the system. In comparison, the abundance of more sensitive species (specialists) declines, or they may disappear from the ecosystem (Vargas-Ríos, 2011). Hence, diversity can be used as an indicator of the impact or recovery by using the quality of habitat, water, soil, or different environmental resources, such as prey in the food chain.

In mangrove ecosystems, diversity quantification of groups, like fish, birds, and aquatic invertebrates, can indicate habitat functions, such as feeding, breeding, and nesting, which mangroves provide to fauna (e. g., migratory birds, prey diversity in food chains, breeding habitat of marine species, bioturbator species, etc.). These species can be related to different hydrological, environmental, and structural variables by using statistical analyses (uni- and multivariate), in addition to the integration of several indices.

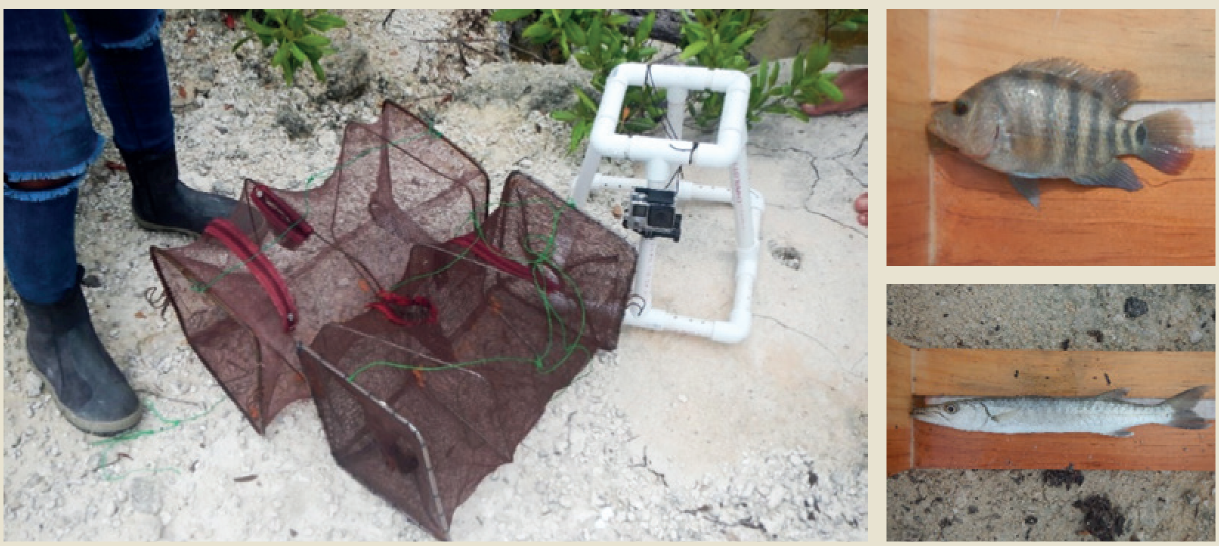


Figure 2.29 — Traps and camera support used for capturing and video recording fish in mangrove canals. Photographs by Daniel Arceo.

It is challenging to have a standardized method when sampling the structural characteristics of mangroves. In the case of fish, depending on depth, the presence of roots and pneumatophores and the sediment type, minnow traps, throw nets, or trawls can be used. When turbidity allows it, subaquatic cameras are also useful (Fig. 2.29). To learn more about the methodology, consult Ebner and Morgan (2013).

Comparing community attributes, such as biomass, abundance, species richness, and diversity, between restoration sites and reference sites, can indicate similarities in ecosystem structure and function (Fasham *et al*., 2005). The diversity in food guilds shows the resources used in each environment, where the presence of many opportunistic or generalist species reveals systems under greater stress. In contrast, relatively specialized guilds, such as zoobenthivores (aquatic invertebrates), insectivores, and icthyovores, show that the ecosystem functions similar to good reference sites.

The same species may behave as a zoobenthivore or carnivore when enough prey is available. However, the same species at a restoration site, where there are fewer resources and an excess of detritus and organic matter may be forced to feed at a lower level in the food chain (e.g., detritophagous) (Hernández-Mendoza *et al*., 2019).

The presence of benthonic organisms may indicate the connection of soil properties, such as humidity, organic matter, salinity, and food availability. This is particularly useful in restoration sites because indicator species can be identified for any specific condition.

For benthic fauna surveys, a corer can be used to extract sediment samples (infauna) and directly count individuals or burrows per square meter on the substrate (crabs). Pitfall traps can also be used (Fig. 2.30).

Figure 2.30 — Benthic organisms on the substrate (mollusks) and the grid square method for counting individuals or burrows per square meter. Photos of Daniel Arceo.

For the monitoring of birds, a census can be conducted to determine the composition and abundance of species that go into the mangrove forest (Ralph *et al*., 1996). Likewise, nest counting can be carried out on mangrove branches to identify the nesting function that mangroves provide. Different species feeding on mangrove roots (waders) or in nearby waters can also be recognized. This way, it is possible to determine how birds use the mangrove, either for feeding, breeding, or resting (Fig. 2.31).

Figure 2.31 — A black-necked stilt nest (*Himantopus mexicanus*) in a restoration area in Progreso, Yucatán, Mexico. Photo by Oscar J. Pérez-Martínez.

Soil

The physicochemical properties of sediments make it possible to integrate hydrological and biological conditions that are associated with the ecological characteristics of mangroves. Sample collection of sediment is recommended to be carried out twice during the first year and on an annual basis after the second year. The values to be assessed are bulk density, organic matter, carbon, nitrogen, and phosphorus (see chapter 2.3.4). Likewise, the thickness and color of sediment layers must be considered because they show a general recovery scenario of the sediment biogeochemical processes.

Landscape analysis

The landscape scale can be used to assess the connectivity within the system and its function within the geomorphological unit through the connection with other ecosystems (Kelly *et al*., 2011; Kuenzer *et al*., 2011). Landscape ecology is an important tool to understand and implement "restoration" actions of ecosystems (Cotler *et al*., 2004). The size and accessibility conditions of the mangrove ecosystem can complicate an in situ assessment to provide sufficient spatial analysis. For this reason, different types of tools must be implemented in order to analyze at a broader spatial scale.

Spatial analysis is used to identify the heterogeneity of the site and the distribution of geographic phenomena, which shows the difference in the dominant territorial units and the critical factors associated with these differences. Remote sensing is a tool to conduct spatial analysis based on landscape unit detection and quantitative assessment. The interpretation of landscape categories can be made by using vegetation indices, which are used to follow up indicators of the changes in vegetation size, cover, and form. (Fig. 2.32). Vegetation indices are quantitative measurements based on digital values that estimate biomass or vegetation health. The techniques for the in situ ecological analysis together with remote sensing helps to accurately identify the variables involved in the processes that define the spatial units.

The landscape analysis assesses the changes in vegetation cover to follow up on the success indicators.

Figure 2.32 — Aerial view with photographs taken with a drone camera of the restoration zone of Progreso, Yucatán, Mexico.

2. Socioeconomic indicators

Socioeconomic criteria evaluate the engagement of different sectors and stakeholders during the entire restoration process and the social benefits provided by the project, whether economic, scientific, cultural, or ecological. The depth of the socioeconomic analysis of the project will depend in part on the participation of social sciences experts and on time and other resource availability (Egan and Estrada, 2013).

The involvement of experts in the area will help create appropriate evaluation tools, such as workshops or interviews, which need to be developed for each community, site, and project. The criteria evaluation is conducted with socioeconomic indicators and is based on the objectives set for each sector. It also includes the assessment of capacity building of those participating in the project and the sustainability of the project over time by communities taking ownership and accountability of the ecosystem and the governance of the project (Fig. 2.33).

Figure 2.33 — Trigger questions to establish the socioeconomic criteria to be evaluated during the mangrove ecological restoration, based on those proposed by Egan and Estrada (2013) and Gann *et al.* (2019).

Four key criteria are suggested based on indicators proposed by Egan and Estrada (2013), the SER principles (Gann *et al*., 2019), and the expertise of the authors of this manual in mangrove ecological restoration projects (Herrera-Silveira *et al*., 2020). To be comparable between projects, certain parameters can be set, such as area (size) of the restoration project, project budget, years of implementation, the relative success of restoration, or other variables of the project status (Table 2.3).

TABLE 2.3 —Socioeconomic criteria and indicators based on those proposed by Egan and Estrada (2013) and Gann *et al*. (2019).

Criteria	Indicators
Collaborative engagement	Number of participating institutions/organizations/sectors
	Created institutional agreements
	Perception of the fulfillment of objectives per sector (representatives)
Social valuation of the ecosystem	Society's perception of the ecosystem
	Community engagement (number of participants and permanence)
	Implementation of workshops on environmental education, training courses: (number of activities and institutions or groups benefitted, attendance)
Economic sustainability	Cost-benefit analysis
	Amount of jobs created/businesses hired
	Self-sustainability of the community (creating opportunities for sustainable use)
	Economic valuation of recovered ecosystem services
	Number of beneficiary families
	Number of day jobs during the different phases of the project
Public policy and funding	Availability of sustainable funding
	Increase of investment in conservation and restoration
	Influence on public policies

Collaborative engagement: The representation of different societal sectors is important during the restoration process, providing sustainability and continuity to the project (Herrera-Silverira *et al*., 2020). These criteria allow for the evaluation of the representation of the different stakeholders involved throughout the restoration project. The evaluation may include the number of institutional arrangements created and the number of participating stakeholders, such as decision-makers, implementers, government institutions, local representatives, etc.

The evaluation may be reported as percentages, the number of representatives, interviews, or evaluations of the objectives fulfilled in the proposed timeframe (Egan and Estrada, 2013).

Social valuation of the ecosystem: Community perception and engagement are critical for the project's continuity through the conservation and maintenance of implemented actions and outcomes at the site (Rönback *et al*., 2007; Walters *et al*., 2008). The engagement and acceptance of the project by community members depend mainly on their social perception of the ecosystem (Stone *et al*., 2008). Therefore, it is necessary to assess the community's current perception of the mangrove, both preserved and degraded, at the beginning of the project. Throughout the project, the strengthening of local capacities is fundamental, which can be achived through workshops on mangrove characteristics, the ecosystem services provided, and restoration principles (Fig. 2.34).

Figure 2.34 — Training workshop "Structure and function of mangrove forests: current concepts and their application in rehabilitation and restoration projects in coastal areas." The course is implemented thanks to the facilities provided by DUMAC within the ecological restoration site, in Celestún, Yucatán, Mexico. Course was organized by CINVESTAV, DUMAC, and CICY.

On the other hand, the restoration site can become a natural classroom for environmental education by offering hikes, workshops, courses, and training for community members, students at different school grades, private and public organizations, and government institutions, among others.

Indicators for this criterion may include the number of community participants (disaggregated by men and women) or institutions/organizations, their participation throughout the project, as well as evaluations from interviews about their perception before and after the project, the number of learning activities or trainings implemented, and its scope in terms of the number of participating individuals and institutions.

Economic sustainability: This is used to determine the benefits rendered to society in economic terms as a result of the restoration, and provides a cost-benefit analysis of the project (Adger *et al*., 1997; Spurgeon, 1998; Walters *et al*., 2008). The economic evaluation of restoration outcomes must consider those activities that directly impact the community in economic, cultural, and recreational terms (Adger *et al*., 1997; Blignaut *et al*., 2014; Wainaina *et al*., 2020), as well as regulation services, such as carbon sequestration, water filtration, or protection against flooding, which have a market value (Adame *et al*., 2014, Narayan *et al*., 2016; Menéndez *et al*., 2020).

In the short-term, the evaluation of the economic impact can be estimated with indicators, such as the number of direct jobs created by the project. In this context, it is important to consider fair and inclusive wages. The engagement of organized women's groups strengthens gender equity, local capacities, and the well-being of local families (Fig. 2.35).

In the long-term, restoring ecological processes provides goods and services that allow the community to be self-sustaining through economic activities, such as traditional fisheries, apiculture, ecotourism, among others (Rönnbäck *et al*., 2007).

On national and international scales, payment for ecosystem services with market value (carbon credits, water filtration, among others) is a success indicator. To this end, it is important to have a proper economic valuation based on the ecological restoration of ecosystem services. The evaluation of economic impact must be related to the objectives set by the project.

Given that the economic evaluation of restored mangrove services involves financial and social investment, it is important to delimit the benefits to be evaluated. If the project objective is to mitigate the effects of climate change, then the evaluation should be based on the amount of carbon sequestered and stored from the restoration. However, it is necessary not to overlook the non-use of mangroves, such as the value of legacy and existence (Sanjurjo and Welsh, 2005).

Figure 2.35 — Organized social groups actively participating in mangrove restoration in the Yucatán peninsula, Mexico. Back row: the "Chelemeras" in Progreso. Front row: "friends of restoration" of Dzilam de Bravo. Photos: Guadalupe Valladares, Jorge Herrera.

Public policy and funding: Institutional arrangements created between stakeholders provide financial sustainability to the project. The joining efforts from all sectors make it possible to fulfill the objectives and expectations for each sector, together in a collaborative learning process. Their engagement and an adequate evaluation of the fulfillment of goals, as well as the proper dissemination of outcomes, can have a long-term influence at a local scale on the funding renewal and the consolidation and development of new projects (Thompson, 2018).

At a regional or national scale, the success of restoration projects may contribute with modifications to public policies favoring mangrove conservation and the increase of investment in mangrove restoration projects (Walters, 1997; Primavera, 2000; Lee *et al*., 2019).

6 Engagement

Ecological restoration practices require engaging communities or indigenous peoples affected by the degradation of the ecosystem. Local stakeholders can positively collaborate in developing restoration projects and benefit from the outcomes (Comín *et al*., 2005). They should be included early on when the project restoration actions and monitoring are being designed.

The engagement of stakeholders has two key aspects: (1) they are important collaborators, and (2) they must contribute with their knowledge of the territory. The knowledge shared may be local, from the residents of the site or nearby; regional, such as experiences from similar actions, or international, from a possible connection of restoration with international programs.

In terms of collaboration, local groups (people, associations, businesses, entities) can contribute with the relevant potential to carry out specific actions, considering that restoration projects often require building permits issued by local authorities.

For the reasons above mentioned, it is important that stakeholders be engaged as early as possible during the planning of the restoration project. In fact, as part of the basic planning draft of the restoration project, one of the first steps is to assess the social acceptance of the project and its actions (Comín, 2002), which highlights the importance of engaging the population and local stakeholders.

Given that the intervention and benefits in all ecosystems are closely connected to human populations, the social component is implied. Nevertheless, the term “socio-ecosystems” is increasingly being used, the concept of “socio-ecological restoration” has even been under discussion (Fernández-Manjarrés *et al*., 2018).

From any perspective, the impact of ecosystem restoration projects has a vital social component because the benefits derived from the actions should positively affect the population. This is highly significant while restoring degraded mangroves due to the multiple environmental services reported locally, regionally, and globally following restoration.

The local benefits of mangrove restoration include employment, protection against weather events, and overall human well-being, which contributes to socioeconomic growth. The social scope of restoration projects also has a regional and global dimension (Fig. 2.36). Mangroves located along the shoreline have a role as regulators for a number of hydrogeomorphological processes and as a shelter for a species of indirect and direct socioeconomic interest.

Figure 2.36 — Birdwatching in mangroves as part of the valuation actions of mangrove ecosystem services.

Governance is another significant aspect of the sustainability of environmental actions. Ecosystem restoration requires integrating multiple legal and administrative aspects and the relationships between participating entities, in addition to the scientific-technical, social, and economic aspects. Thus, a successful restoration requires including regulations and good governance practices in the planning, implementation, and evaluation of project activities (Sapkota *et al*., 2018).

Timely, detailed, and precise information of objectives and progress of a restoration project, as well as of the complications that should arise, are essential for adequate governance. The restoration of degraded ecosystems can be promoted and implemented by any entity or individual interested in doing so. In any case, compliance with regulations of each site where actions are planned is vital.

Therefore, it is critical to have all the necessary permits before putting actions in motion. Maintaining smooth and proper relationships between official entities responsible for administrative control and environmental legislation within the relevant regulatory framework is also important.

Likewise, it is also important, where entities responsible for administrative and environmental legislation for implementing actions and restoration projects should favor a prompt and straightforward process regarding their communication with project promoters and implementers.

All aspects of mangrove ecological restoration are useful in the engagement of society, socialization, and governance of projects. Experiences and lessons learned from implementing this type of project are useful for the education and capacity building of people, especially at a local scale. During the stages of recovering mangrove cover, the project favors the engagement of society, the sharing of experiences, and project governance.

Local capacities are strengthened by engaging communities in the process of mangrove restoration because participants become organized, acquire experience, and consolidate their mangrove knowledge. Successful ecological restoration projects include scientific-technical, social, economic, and governance aspects, which are the four pillars of sustainability (Fig. 2.37).

Before, during, and after the restoration project

Engagement	Socialization	Governance
The need to positively engage local/regional agents in actions (inform, consult, educate, participate)	Sharing experiences, benefits, form (future of the restored space) and substance (efficiency and equity of restoration benefits).	Communication, distribution of roles among participants, transparency.

Dissemination: popular, educational, and scientific

Figure 2.37. Engagement, awareness, and governance of ecological restoration of mangroves.

3. Mangrove restoration in the Wider Caribbean

A systematic search was carried out in free access websites using search engines, such as Google and Google Scholar, for open access scholarly publications, theses, technical reports, conference reports, journal pieces, and webpages that mentioned ecological restoration projects in mangrove ecosystems of the Wider Caribbean region (Large Marine Ecosystems of the Gulf of Mexico, the Caribbean Sea, and the North Brazil Shelf). A total of 158 sources were collected, including primary and gray literature. Of these, only 112 explicitly mentioned mangrove restoration and included data incorporated in the analysis.

However, there are many more unpublished works or only available in journals with a paid subscription. The reviewed restoration projects took place in 27 countries and territories from 1979 to 2019. Of these, 74.1% are found in the continental region (83), and 25.9% are in insular areas (29). The Gulf of Mexico LME presents the most significant percentage of projects (53.6%), followed by the Caribbean Sea LME (42.0%), and only 4.5% on the North Brazil Shelf LME (Fig. 3.1).

The countries with the highest percentage of restoration projects are Mexico (57.1%), Colombia, the United States, Saint Martin (3.6% each), and jointly the Bahamas, and Saint Vincent and the Grenadines (2.7% of the projects each) (Fig. 3.1). It is worth noting that the French territory of Saint Martin holds 75% of the projects implemented in the country, while the Dutch territory holds 25%. It is not possible to identify a specific reason for the significant differences in the available information. However, some might be that the data is stored in internal institutional reports or is included in academic dissertations, confidentiality clauses of funding sources that prevent information from being published, or the outcomes are not published because they did not achieve the project goals, among other reasons.

Figure 3.1 — Proportion of mangrove restoration projects in every country that belongs to the Wider Caribbean. A red box represents the countries of the Gulf of Mexico LME region, the yellow box represents the countries in the Caribbean Sea LME, and the green boxes represent the countries in the North Brazil Shelf LME.

Drivers of degradation in the region

Drivers of degradation in mangrove ecosystems in the region are closely related to the uses and customs of communities, as well as with economic growth model of the country. In the Wider Caribbean, the main threats recorded in project reports were changes in land use, urban development, timber extraction, natural events, and mining and hydrocarbon industry (Table 3.1). However, some reports do not mention the drivers of degradation. Examples of drivers of mangrove degradation that are common across the region include highways and roads, changes in land use to urban-tourism, extreme natural events, and hydrological changes (Table 3.1). Although most of the mangrove species in the Caribbean region are protected under international agreements, and each country's legislation, the change in land use and the extraction of timber products by the communities are common problems across the Wider Caribbean region.

TABLE 3.1 — Threats and drivers of degradation in mangrove ecosystems in the Wider Caribbean

Threat	Driver	Country
Change in soil use	Installation of shrimp farming	Brazil[1]
	Livestock farming and incidental logging	Guyana[2]
	Clearing	Martinique[3], Honduras[14] and Guatemala[15]
Urban development	Road construction	Mexico[4,5]
	Bridge construction	Aruba[6]
Extraction of timber products	Carbon production	Grenada[7], Jamaica[8] and Guatemala[14]
Natural events	Hurricane damage	Puerto Rico[9] and Mexico[10]
	Canal silting	Mexico[11]
Industry	Mining and resource extraction	Venezuela[12]
	Oil spills	Panama[13]

[1]Ferreira, Ganade and de Attayde (2015); [2]Caribbean Environment Programme (2019); [3] http://evenements.developpement-durable.gouv.fr/campagnes/evenement/11359; [4]Herrera-Silveira *et al*., (2012); [5]Alonzo-Parra (2011); [6]Dutch Caribbean Nature Alliance (2017); [7]Heemsoth (2021); [8]Grenadian – German Pilot Programme (2018); [9]Society of Ecological Restoration (1994); [10]Echeverría-Ávila *et al*., (2019); [11]PRONATURA (2013); [12]Society of Ecological Restoration (2004b); [13]Outterson (2014); [14]CEM (2021); [15]MAR FUND (2021).

What has been done to restore mangroves in the regions of the Mesoamerican Reef System and the Wider Caribbean?

The number of mangrove restoration projects indicates the importance of conservation and restoration of this ecosystem in the region. Some measures have been taken; for example, natural protected areas have been declared, species are under some protection status (law, standard, regulation, national strategy), public policies have been implemented for restoration strategies to recovering mangrove ecosystems with different objectives. Moreover, projects have been implemented in coordination with organizations or institutions as a measure to offset environmental impacts, and more recently to restore lost ecosystem services, such as to mitigate the impact of hydrometeorological events (storms, hurricanes, and flooding).

According to the literature review, restoration actions in the Wider Caribbean region began at the end of the 1970s, with reforestation being the main restoration action (Fig 3.2). From the 1980s, restoration actions were implemented in the Gulf of Mexico LME region. In addition to reforestation, other activities have been implemented, including hydrological rehabilitation, mainly by restoring water flow between mangroves and neighboring ecosystems (Fig 3.2). Up until the 1990s, restoration actions began to be implemented with hydrological rehabilitation and reforestation, chiefly to reduce salinity and favor planting, which in some cases came from nurseries (Fig. 3.2).

Since the year 2000, mangrove restoration projects were identified in the North Brazil Shelf LME. The single or combined use of topographical management is included in restoration actions to temporarily buffer the changes in flooding levels in mangroves. It is also observed that the number of mangrove restoration projects has increased since the year 2000, where most take place in the Gulf of Mexico LME (Fig. 3.2). These results are probably biased due to the availability of project reports and open data.

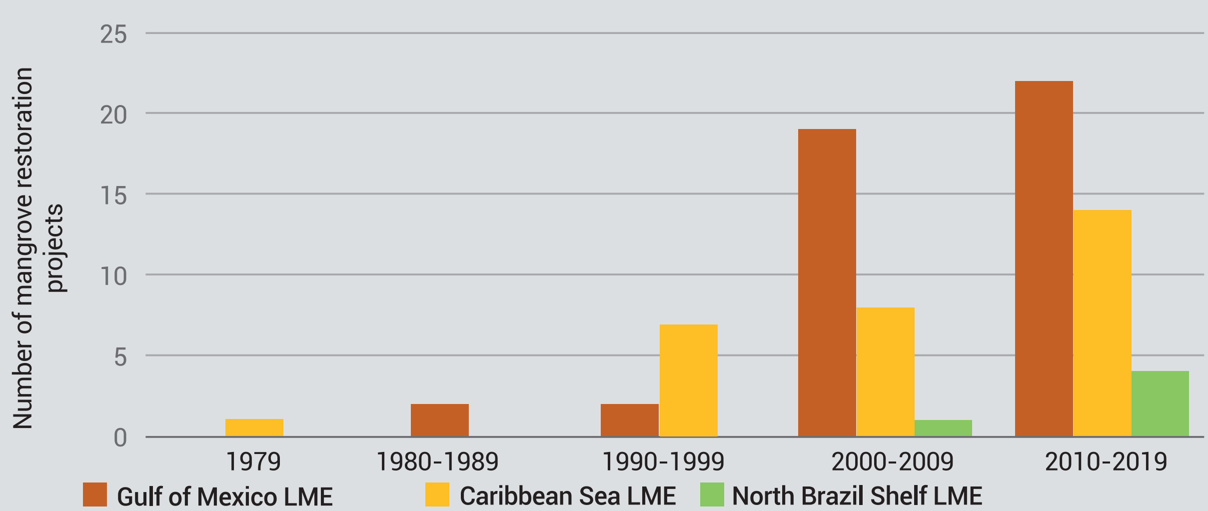


Figure 3.2 — Number of mangrove restoration projects in the three regions of the Wider Caribbean over time.

Further analyses revealed that mangrove restoration actions use reforestation as the main activity, followed by hydrological rehabilitation (Fig. 3.3). Some projects combine actions; for example, reforestation and hydrological rehabilitation is the most used combination in the Gulf of Mexico and the Caribbean Sea LMEs. In the North Brazil Shelf LME, the most common combination is reforestation and topography modification (Fig. 3.3). On the other hand, the application of all three restoration strategies together has only been used in the Gulf of Mexico LME region (Fig. 3.3).

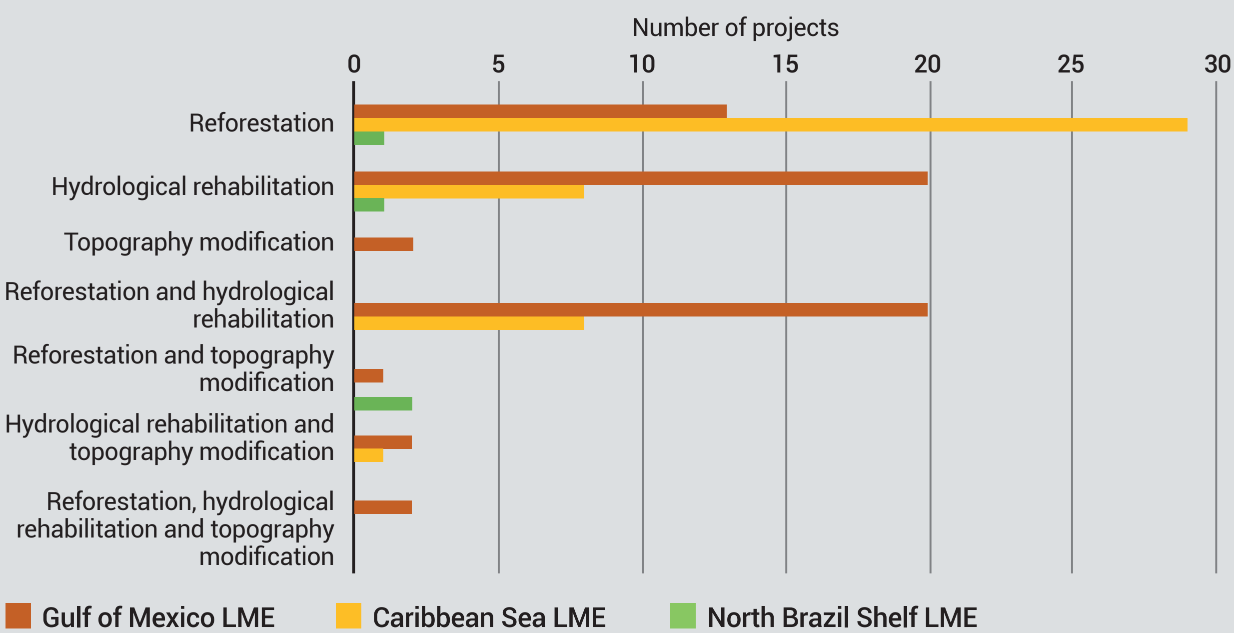


Figure 3.3 — Mangrove reforestation actions used in each region of the Wider Caribbean.

How many hectares of mangrove have been intervened for restoration?

Analyzed information sources show that in the last 40 years, approximately 51,355 hectares (ha) have been part of mangrove restoration projects in the region of the Wider Caribbean. The size of mangrove restoration projects range from 0.1 ha in Baywatch Marina, Martinique, to 35,000 ha in La Ciénaga Grande de Santa Marta, in the Colombian Caribbean. Most restoration actions, identified in the literature review, were implemented at a local level in areas smaller than 100 ha. The rest of the projects are implemented at a landscape or regional scale (over 100 ha) (Fig. 3.4). The project of La Ciénaga Grande de Santa Marta in Colombia in the Caribbean Sea LME is the region with the greatest area (46,902 ha) of mangrove undergiong restoration. However, the Gulf of Mexico LME has the greatest number of restoration projects implemented in the region, but only 4,311 ha are reported, and only 142 ha under restoration was reported for the North Brazil Shelf LME. In the MAR region, 312 ha have been restored, the majority of which occurred in Mexico.

The area where restoration actions have been implemented, hydrological rehabilitation, reforestation, and the combination of these two activities vary considerably in size, in which the largests areas under restoration are 47,157 ha, 1,710 ha, and 2,087 ha, respectively. Together, these actions represent over 98% of the mangrove area undergoing restoration in the regions of the Gulf of Mexico LME and the Caribbean Sea LME (Fig. 3.5). Although there have been reforestation and hydrological rehabilitation actions in the North Brazil Shelf LME, it was not possible to find results for these actions. In the MAR region, reforestation and hydrological rehabilitation combined are the most implemented actions, and only 219 ha in reforestation and 92 ha in hydrological rehabilitation.

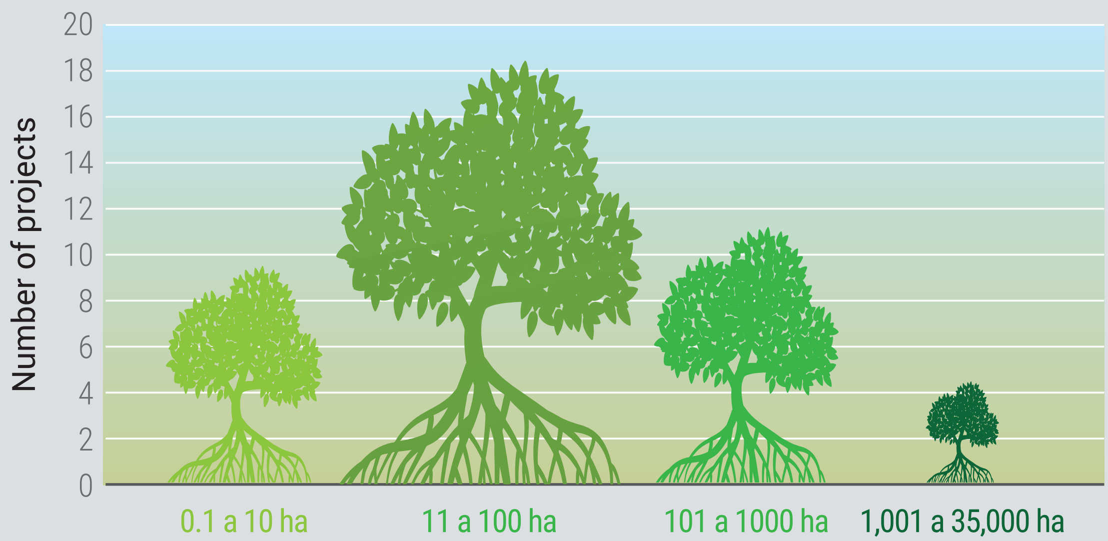


Figure 3.4 — Distribution ranges of the number of restored hectares reported in each retrieved work in the Wider Caribbean region.

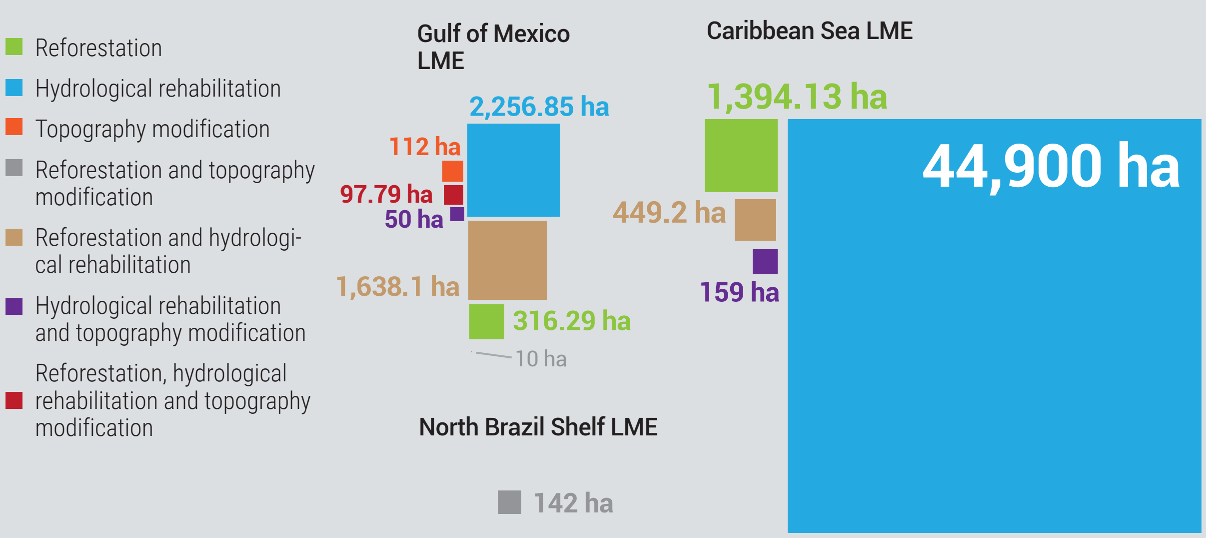


Figure 3.5 — Restored hectares of mangrove for each action used individually or combined in different regions of the Wider Caribbean.

What has been the success of mangrove restoration in the Wider Caribbean region?

It is considered that restoration projects are more successful if social, government, non-government, and technical-scientific sectors are involved. In the Wider Caribbean region, 85% of information sources mention this aspect; however, it is uncommon that these reports specifically mention the participation of different sectors, either individually or together.

The first mangrove restoration projects in the region were implemented by local communities following a trial-and-error approach with funds from the private sector, NGOs, and national governments.

Later, to increase restoration success, academia was involved through universities, research centers, and specialized departments of ministries and government secretariats. This involvement resulted in better restoration strategies and adaptations for each particular region. Capacity building was also promoted in implementing groups of restoration actions, many of them taught by members of communities near the projects.

The involvement of the academic sector in restoration projects contributed to the increase of knowledge on mangrove restoration ecology. Every restoration project has its own particular characteristics; thus, it is an "experiment" to identify the causes of the extent of the success in restoration projects during the evaluation.

Moreover, the knowledge provided by academia, the government and NGOs has formalized the empirical understanding of communities on mangroves and restoration. Today we know that groups of men, women, and mixed groups that started as workers carrying out restoration actions are now organized in independent cooperatives of trained restorers.

Although these groups have been coordinated mainly by NGOs and academia, groups formed in the past years are now more independent, which, besides implementing restoration tasks, also carry out monitoring and natural resource management activities at the site. Some examples of these groups are shown in Table 3.2.

TABLE 3.2 — List of some of the mangrove restoration groups working in the Wider Caribbean region

Country	Restoration Groups	Activities
Mexico	Restoration Community of Aguada island	Reforestation and hydrological rehabilitation
Mexico	Community members of Villa Aguada island	Reforestation and hydrological rehabilitation
Mexico	Day workers of the communities of Sodzil, Chunkanán, Pomuch, and Hecelchakán	Reforestation, hydrological reforestation, and topographic modification
Mexico	Common landholders of Nunkiní	Monitoring
Mexico	Residents of Higuerillas-Mezquital village, San Fernando municipality, and Francisco J. Mujica common land	Reforestation and environmental education
Mexico	Community of Bahamitas	Hydrological rehabilitation
Mexico	Local community of Laguna de Términos	Hydrological rehabilitation
Mexico	Communities of El Pájaro, Mano Perdida, Pérez y Jiménez, and La Guadalupe	Reforestation, hydrological rehabilitation, and topography modification
Mexico	Day workers of Sodzil, Chunkanán, Pomuch, and Hecelchakán locations	Reforestation and hydrological rehabilitation
Mexico	Cooperative Society of Fishermen of La Ribera de Sontecomapan	Reforestation
Mexico	Biosphere Reserve Civil Association and Forestry Association of Los Tuxtlas	Reforestation
Mexico	Community members of La Nueva Reforma	Reforestation
Mexico	Community members of El Pájaro	Reforestation
Mexico	Community members of Cárdenas	Reforestation
Mexico	Women's group of the common land Moral and Mosquitero	Reforestation
Mexico	United Chelemeros for the protection and restoration of mangrove	Reforestation, hydrological rehabilitation and topography modification, and environmental education
Belize	Coralive	Reforestation and environmental education
Belize	Fragments of hope	Reforestation, natural resource management, and environmental education
Belize	Residents of Placencia Village	Reforestation and surveillance

Belize	Residents of Corozal	Reforestation and surveillance
Belize	Residents of San Pedro	Reforestation and surveillance
Belize	Residents of Belize city	Reforestation and surveillance
Belize	Placencia Tour Guide Association	Reforestation
Belize	Southern Environmental Association	Reforestation
Belize	Coastal Zone Management Authority and Institute	Reforestation, natural resource management
Guatemala	Local Mangrove Roundtable (MLM, for its initials in Spanish) El Golfete, Río Dulce	Reforestation
Guatemala	Ak' Tenamit	Reforestation and environmental education
Guatemala	Residents of the community Cayo Quemado	Reforestation and natural resource management
Guatemala	Residents of the community La Angostura	Reforestation and surveillance
Guatemala	Residents of the community Barra Lámpara	Reforestation and surveillance
Guatemala	Asociación Maya Probienestar Rural del Área Sarstún	Reforestation
Guatemala	Residents of the community Barra Sarstún	Reforestation and surveillance
Guatemala	Residents of the community of San Juan	Reforestation and surveillance
Honduras	Recuperación Bejucales Group	Reforestation
Honduras	Bay Islands Conservation Association (BICA-Guanaja)	Reforestation and environmental education
Honduras	Residents of the community Lis Lis	Reforestation and natural resource management
Honduras	Residents of the community Balfate	Reforestation and natural resource management
Honduras	Community of Estero Prieto/Las Flores	Reforestation
Colombia	Asociación sostenible de mangleros y pescadores (Boca Cerrada)	Monitoring
Colombia	ASOAMANGLEBAL (Asociación ambientalista de mangleros de la balsa)	Reforestation and natural resource management
Colombia	ASOMATIC (Asociación de mangleros de tinajones de composteros de san bernardo del viento)	Reforestation and natural resource management
Colombia	ASOMAGPESTIN (Asociación de pescadores y mangleros de tinajones)	Reforestation and natural resource managemen
Colombia	ASOMASAN (Asociación ambientalista de mangleros de san bernardo del viento)	Reforestation and natural resource management
Colombia	ASOMAGRO (Asociación de mangleros agroecológicos de san antero)	Reforestation and natural resource management

Colombia	COOPROCAÑO (Cooperativa de productores y comercializadores agrícolas de caño lobo)	Reforestation and natural resource management
Colombia	ASMADECOS (Asociación de mangleros para el desarrollo del ecoturismo en el antiguo delta del rio Sinú)	Reforestation and natural resource management
Colombia	COMASCAL (Comité de mangleros solidarios de Caño Lobo)	Reforestation and natural resource management
Colombia	ASOMAUSAN (Asociación de mangleros unidos de San Antero)	Reforestation and natural resource management
Colombia	ASOMAPEBCA (Asociación de mangleros y pescadores de base de cantarillo)	Reforestation and natural resource management
Colombia	ASOMAPESCA (Asociación de mangleros y pescadores de Caño Lobo)	Reforestation and natural resource management
Colombia	ASOMASANBV (Asociación ambientalista de mangleros del municipio de San Bernardo del Viento)	Reforestation and natural resource management
Colombia	ASOAGROCHI (Asociación ambientalista agrícola del corregimiento de Chiqui del municipio de San Bernardo)	Reforestation and natural resource management
Colombia	Pobladores de Tasajera, Pueblo Viejo, Isla del Rosario, Palmira, Bocas de Cataca, Buena Vista, El Morro, y los caseríos del Caño Clarín.	Reforestation and natural resource management
Jamaica	Local committee of the mangrove reforestation Project in Kingston Harbour	Reforestation
Haiti	Residents of the Fonds-Verrettes commune, Cayes-Jacmel commune, and de Gros Cheval location	Reforestation and environmental education
Haiti	Members of the coastal watershed Aquin and Saint Louis du Sud	Environmental education
Haiti	Aquin community	Reforestation
Cuba	Residents of Playa Cajío	Reforestation and hydrological rehabilitation
Saint Lucia	Ma Koté community	Reforestation and hydrological rehabilitation
Guyana	Producer women's group of the Guyana Mangrove Reserve	Reforestation and environmental education
Guyana	Neighboring communities of West Coast Berbice	Reforestation and natural resource management
Suriname	Weg naar Zee community	Reforestation and natural resource management

According to the literature reviewed, only 13% of the analyzed information sources address the number of hectares of degraded mangrove found when restoration actions began, as well as the number of restored hectares. The rest of the sources lack one or both components. The absence of data on the number of hectares of mangroves under restoration or already restored makes it difficult to analyze the restoration success at a regional level.

Of the degraded or impacted hectares mentioned in the reviewed information sources (112), 25% described the affected area or the area to be restored. The Gulf of Mexico LME region shows the highest percentage of documents containing this information (64%), followed by the Caribbean Sea LME (32%), and a lower percentage in the North Brazil Shelf LME (4%).

Regarding mangrove ecological restoration derived from implemented restoration actions, only 43 (38%) of the projects mentioned the number of recovered hectares. Of these, the Gulf of Mexico LME reports the highest percentage of documents containing this information (68%), while the North Brazil Shelf LME shows a lower percentage (2%) (Fig. 3.6). Particularly, the Gulf of Mexico LME shows the highest percentage of information sources (48%) compared to the regions of the Caribbean Sea LME and the North Brazil Shelf LME, which is lower than 30% in both cases (Fig. 3.6).

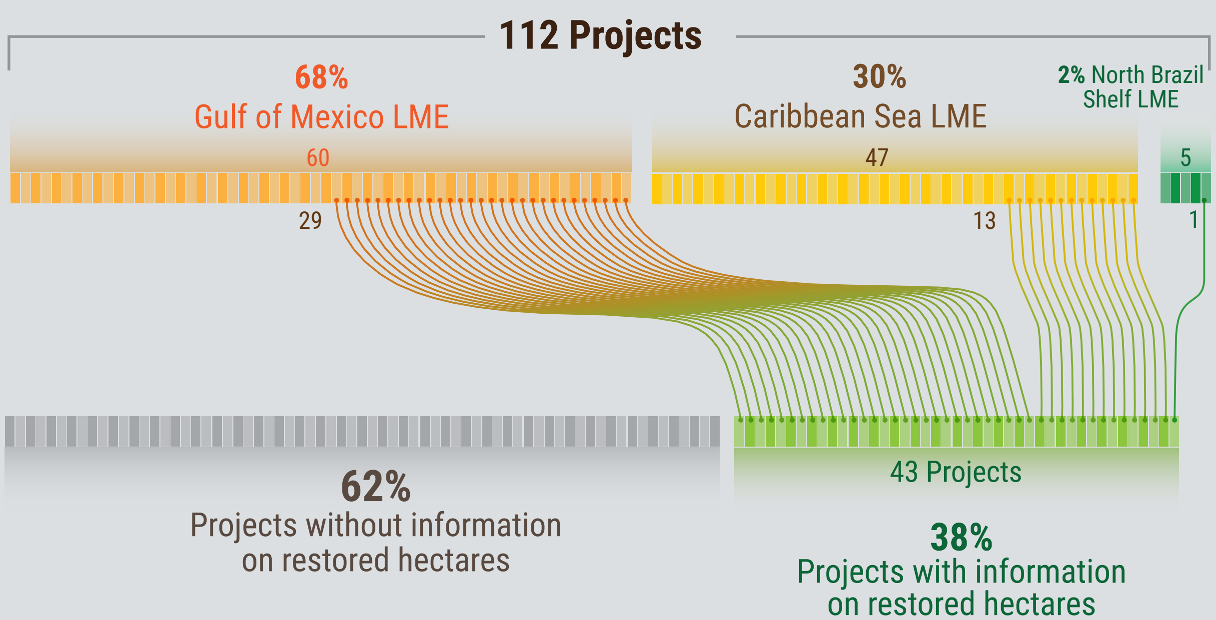


Figure 3.6 — Proportion of information sources that provide data regarding the number of hectares restored in each region of the Wider Caribbean. The number of sources of information that report the restored hectares for each region of the Greater Caribbean is specifically shown.

What are the costs of mangrove restoration in the Wider Caribbean region?

In terms of costs of restoration projects, there is high variability in the ratio of restored hectares to cost. It is important to mention that outcomes represent the total cost of projects adjusted according to the inflation for 2021.

Restoration costs include daily wages, restoration actions (reforestation and hydrological rehabilitation or topography modification), nursery construction when necessary, capacity-building, etc.

The cost of the monitoring program of restoration actions, as a key stage of the strategy described in earlier chapters of this manual, is only considered for the project's duration, evaluating some of the suggested variables in the monitoring chapter of this manual. The cost of mangrove restoration actions per hectare in the Gulf of Mexico LME varied between USD 2,000 and 120,000, the latter in West Lake, Florida (USA), under the project Mangrove Restoration at West Lake (Broward County) where 500 ha of mangrove were restored during 11 years through hydrological rehabilitation (Fig. 3.7).

In the case of the Caribbean Sea LME, the cost per hectare ranged from USD 2,050 to 25,000, the latter in Culebra, Culebra Island (Puerto Rico), where 8.1 ha were restored through reforestation of more than 4,000 individuals of R. mangle as part of the project Culebra Island: Puerto del Manglar Red Mangrove Restoration (Fig. 3.7). It was not possible to obtain investment figures for the site with the largest area of the region (Ciénaga Grande de Santa Marta, Colombia), but it is probably the highest in the region.

The high variability of costs in mangrove restoration is mainly related to the type of action or actions implemented. Regarding the hydrological rehabilitation costs, besides labor and the necessary supplies (shovels, picks, bags) to build canals by hand, there are expenses required to cover the lease of machinery for digging canals, to move large amounts of sediment, as well as the construction of bases and concrete pipes to build culverts, for instance, on roads.

In the case of reforestation, the cost increases due to the construction and maintenance of nurseries, as well as the type of material used for planting. When comparing projects with hydrological rehabilitation actions, it is noticeable that there is a tendency that while restored hectares increase, costs rise. However, this trend is not so clear when reforestation actions are applied (Fig. 3.8).

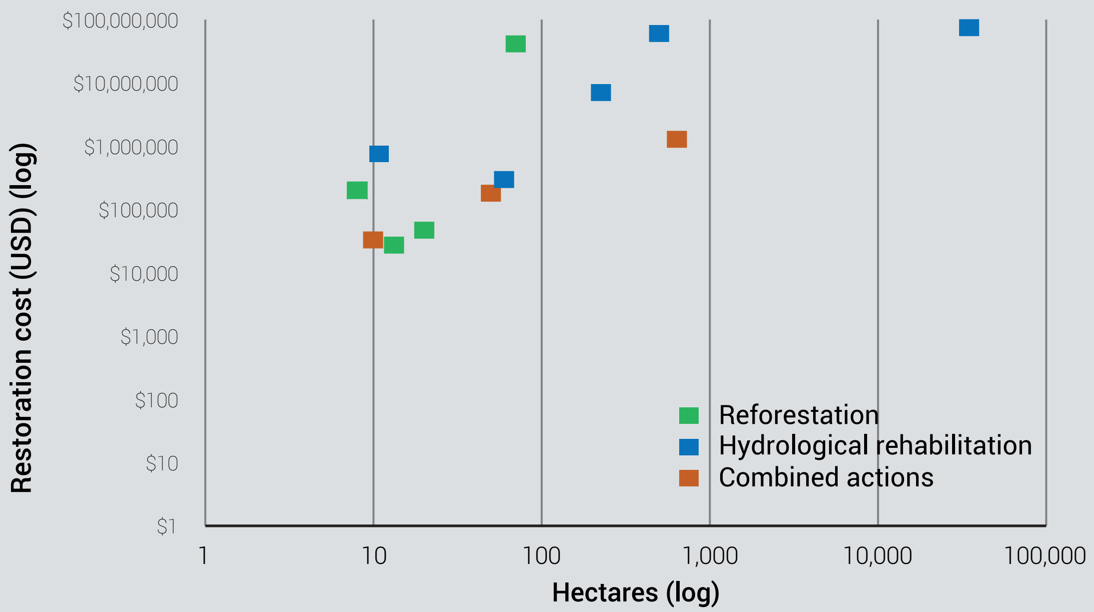


Figure 3.7 — Restoration cost of one hectare of mangrove for one of the actions used individually or combined. Costs are expressed in dollars based on the corresponding inflation for 2021 and are presented in logarithm base 10 for comparison.

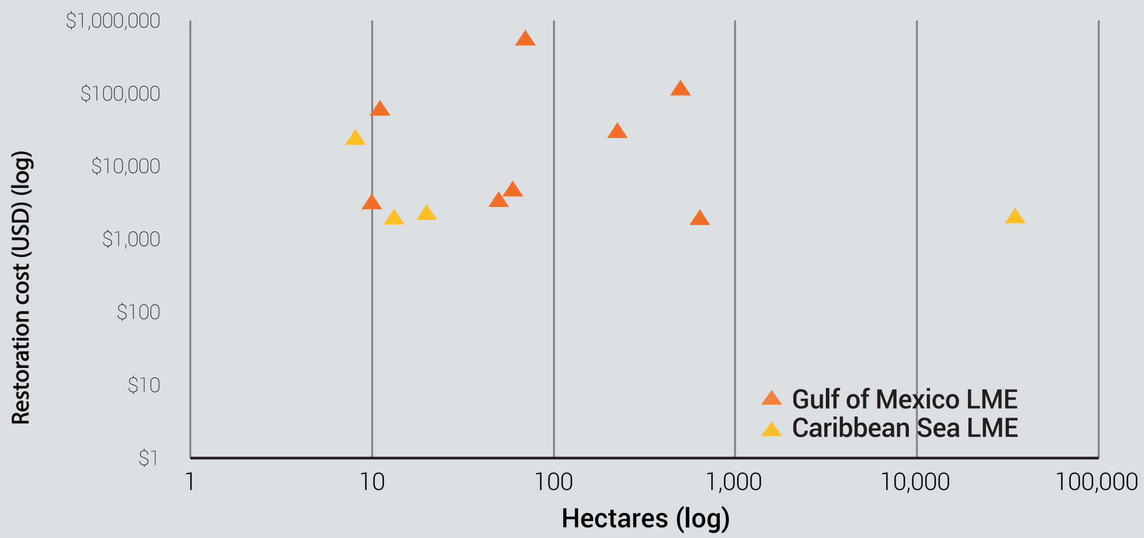


Figure 3.8 — Restoration cost per one hectare of mangrove for each region in the Wider Caribbean. The North Brazil Shelf LME is not included because there is no information found in reviewed works. Costs are expressed in dollars adjusted to the corresponding inflation for 2021 and expressed in logarithm base 10 from the differences in extent.

Final considerations

The drivers of mangrove deterioration are diverse and are linked to socioeconomic characteristics of each country. Some of the leading causes are urban development, tourism, timber extraction, primary sector activities, mining and hydrocarbon industry, and natural events. However, the change in land use is the most frequent and has a stronger impact upon the area of degraded mangrove.

With the goal to mitigate the consequences of these threats since the 1970s, there has been an incentive to create, systematize, and implement activities that allow for the recovery of mangroves that have been degraded or destroyed in the Wider Caribbean region. The Gulf of Mexico is where the highest number of restoration projects have been implemented. In contrast, the Caribbean Sea region has had the highest number of hectares involved in restoration actions.

Restoration actions have evolved from a trial-and-error approach to a more structured strategy where synergies between actors (social, government, academic, and funders) have produced better outcomes than individual efforts. These actions can currently be classified under three approaches: hydrological rehabilitation, topographic rehabilitation, and reforestation, the latter has been implemented more frequently. Current restoration trends are shifting towards a combination of actions, such as hydrological rehabilitation as the most used.

In regard to the size of the area to be restored by restoration projects, it is determined based on the set objectives and the available resources. Projects that restore sites no larger than 100 ha are the most common. Restoration costs change according to different factors, such as location, area to be restored, time required, cost of supplies in the region, and the living standards in each region, country, among other aspects. According to this review, the cost of mangrove restoration in the Wider Caribbean region ranges from USD 2,000 to 120,000 per hectare (Fig. 3.7 and 3.8).

Recommendations

- Increase the number of mangrove restoration projects and hectares in the Wider Caribbean region, considering the deforestation rates at which they are subject.
- Mangrove restoration projects must follow a strategy that maximizes the cost-benefit ratio. The proposal in this manual is an alternative that has proven to be highly efficient.
- Restoration projects should seek to build synergies between society, government, academia, and financial institutions.
- Efforts to should be made to strengthern the capcities of local communities, including them in monitoring programs, and results should be disseminated.
- Implement activities at the restored mangrove site involving local communities that favor project ownership by communities and the continuity of ecosystem functions.
- Make regional and national emergency appeals for the protection of mangrove ecosystems.
- Promote intersectoral and interinstitutional cooperation to optimize resources and avoid duplication of actions in specific regions.

Glossary

Adaptive management	Is a process of experimentation, learning, and continuous improvement informed by successes and mistakes.
Anoxic conditions	Environments found in seawater, freshwater, or underground water in which dissolved oxygen is absent.
Autecology	This branch of ecology is the study of how living organisms adapt to their environment. It allows us to understand how species survive according to their habitat.
Bathymetry	The topographic survey of subaquatic depth or land covered by water bodies, such as the sea bottom, waterways, lakes, rivers, reservoirs, etc.
Benthic organisms	Organisms attached or buried in a substrate at the bottom of a water body.
Biogeochemical cycles	Are the processes by which the elements necessary to life (e. g., C, N, P) flow between living organisms and the environment.
Biomass	The total amount of matter (the non-aqueous component is often expressed as dry mass) from living organisms.
Brackish	Water with more salinity than freshwater, but less than seawater, approximately 0.5 to 17.0 parts per thousand.
Bulk density	Is the weight ratio of dry soil (mass) and its volume that includes the volume of particles and the porosity between particles.

Carbon credits	Mechanisms created as a national and international effort to reduce the concentration increase of greenhouse gases (GHG). One carbon credit is equal to one tonne of carbon equivalent.
Carbon sink	Are deposits in which carbon dioxide is sequestered, preventing it from being released into the atmosphere.
Clays	Fine sediment particles (<0.002 mm), which do not drain or dry easily, sticks to fingers, and contains good nutrient reserves.
Climate change	Is the modification of climate that has occurred compared to its history on a regional and global scale. It is directly or indirectly attributed to human activity.
Connectivity	Describes how the distribution and quality of elements in a landscape affect the movement of organisms between habitats.
Dredging	Is the operation that consists of clearing and deepening a body of water by removing rocks, sand, and sediment.
Degraded ecosystem	An ecosystem whose diversity, productivity, and ecological function has been reduced to the extent that it makes it unlikely to be able to recover if rehabilitation or restoration measures are not adopted.
Degraded reference	An ecosystem or a portion of it in similar condition as those that need to be restored. It is considered a model to prove that it is thanks to restoration that the restored ecosystem has improved.
Desilting	Elimination or removal of accumulated sediments blocking a conduct or canal.
Detritophages	Organisms that feed on dead organic matter.
Detritus	Debris resulting from the decomposition of organic matter.
Ecological restoration	Consists of carrying out a process for the recovery of an ecosystem that has been degraded, damaged, or destroyed, and that can return to its original state.
Ecosystem	Is a system with interactions between living organisms and their physical environment.
Ecosystem resilience	The natural ability of the environment to return to its initial condition after sustaining a disturbance.
Ecosystem services	Are the benefits that people obtain from nature. These benefits can be in the form of assets, goods, or services.
Enabling species	Species that modify a habitat, thus benefiting the growth, survival, and development of other species.

Erosion	Series of processes that cause the soil to wear away from the effect of extreme natural agents, especially water and wind.
Fruiting	Producing fruit.
Governance	The way to regulate a society in which the government, civil society, different institutions interact to resolve matters of public interest.
Guilds	Groups of species that use the same kind of environmental resources in a similar way.
Greenhouse gases (GHG)	Refers to the gases emitted naturally and anthropogenically (from human activity) that accumulate in the atmosphere of Earth and absorb the sun's infrared energy. This creates the known greenhouse effect, which contributes to the global warming of the planet.
Heterogeneous environment	A space with climatic, topographic, and edaphic properties varying in time and space, favoring local adaptations and clinal genetic variation.
Hydroperiod	Is the pattern that results from the flooding level, frequency, and duration in a specific area.
Inorganic nutrients	Compounds essential for the growth of living organisms that do not have carbon in their chemical structure.
Interspecific interactions	Occurs when individuals of one species interact with individuals of other species.
Interstitial water	Groundwater found between rocks and sediments.
Intraspecific interactions	Occurs when individuals of one species interact amongst themselves.
Juvenile	An organism that has not yet reached the adult form (is not sexually mature). In mangroves, juveniles are considered those who have reached a height taller than 50 cm, with a diameter less than 2.5 cm.
Microtopography	Is a characteristic of the land surface in which minor variations are measured, often measuring only one or two centimeters. It is one of the main regulators of the hydroperiod.
Mitigation	Is an abatement or reduction action of the negative environmental impact caused by different activities in order to lower it to tolerable or admitted limits of current standards.
Morphological adaptations	Are the changes that organisms develop in their external structure that allow them to adapt better to their habitat.

Nature-based Solutions (NbS)	Actions use ecosystems and the services they provide to address diverse societal challenges, such as climate change, food security, or disaster risk.
Organic matter	It is generated from organic compounds that come from the remains of organisms that once were alive, such as plants, animals, and their waste products in the natural environment.
Oxidation of organic matter	Occurs when stored carbon as organic matter in the soil releases CO_2 due to aerobic conditions caused by the interruption of water flows.
Phenology	Is the study of the development or cycles of living beings related to climatic and environmental variations.
Pneumatophore	Are roots that act as a gas exchange organ since they occur in plants that grow in oxygen-deficient soils. This is possible because they grow in the opposite direction of the soil.
Preserved reference	Is an ecosystem with developed vegetation, without impacts that provide ecosystem services. It is considered a model site to further replicate after implementing an ecological restoration project.
Productivity	The capacity of an organism to generate organic material.
Propagules	Part or structure of an organism produced sexually or asexually, capable of developing a new identical organism as the original.
Secondary succession	Is the process of change in time through which a community sequentially replaces another until it is completely established.
Sediment	Deposit or accumulation of particles (sand, gravel, silt, or mud) transported by air or water to the soil of wetlands. It is formed by layers on the earth's surface.
Sedimentation	Process of suspended matter in water being deposited or settled due to the effect of gravity.
Seedling	Developmental stage that starts when a seed breaks its dormancy and germinates. In this case, the mangrove is born and develops until it reaches a height of 50 cm.
Silt	Sediment particles of fine grade size ranging from 0.002 to 0.006 mm, coarse to the touch, dry relatively fast, and are non-sticky.
Soil texture	It is the soil composition determined by the size of particles that make it up. The clumping determines the pattern of pores that influence the flow of water, aeration, and porosity of the sediment.

Stored carbon	Is the total amount of carbon contained by the biomass.
Sustainable development	Meeting the basic needs of the current population that does not cause harm to the environment and without compromising the needs of future generations.
Sustainable Development Goals (SDG)	An initiative launched by the United Nations to end poverty, protect the planet, and ensure that all people live in peace and prosperity by 2030.
Topographic level	A measure established according to the average sea level, taking as reference a body of water (lagoon, river, marine zone, etc.), as well as the hydrology of the site of interest.
Vulnerability	It refers to the degree of resistance of a system, sub-system, or component of a system facing global warming and biodiversity loss, caused directly or indirectly by human activity or natural phenomena.

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