

MANGROVE ECOLOGICAL RESTORATION GUIDE: LESSONS LEARNED



MANGROVE RESTORATION: WHY NOW?, WHY MANGROVE?

- The mangrove, as an amphibious ecosystem between the sea and the land, has suffered from the impacts of both sides. On the side of the sea: erosion, storms and increased sea level; and on the coastal side: deforestation, fires and agricultural management in coastal basins with consequences on water resources that affect the mangrove.
- Central America and the Caribbean are regions of the planet where there is a significant increase in the intensity and frequency of extreme weather events. The hurricanes, drought and floods, have severe effects on the stability of coastal ecosystems and their ecosystem services.
- The Mesoamerican and Caribbean region includes a large number of State Islands whose ecological, economic and social stability depend on the well-being of their coastal territories and their ecosystems such as mangroves. So, it is necessary, more than ever, to promote Nature-Based Options such as Green Infrastructure, as a way of protecting the coast, their societies, and their quality of life.
- Blue carbon ecosystems provide a large numbers of ecosystem services (protection, food provision, CO₂ capture, wood production, habitat for biodiversity). Restoring them is a fundamental benefit for society. Currently, plans for risk reduction and reconstruction of the mangrove after extreme events do not include Nature-Based Solutions.
- The United Nations has declared 2021–2030 as the Decade of Ecological Restoration. The region has seen an increase in reef restoration, but much less effort has been seen in coastal forests, such as mangroves, salt marshes and seagrasses (which make up blue carbon).
- The region has shown its commitment to the Bonn Challenge and its 20 x 20 Initiative, which represents an excellent opportunity to increase restoration of degraded or deforested mangrove. However, the 20 x 20 Initiative does not include mangroves among its restoration goals. This guide is intended to support that window of opportunity.
- The governments of the region and governmental and non-governmental institutions will benefit from this guide, which offers a coherent vision of the four necessary components for a restorative process, where hydrological recovery plays one of the main roles (and not reforestation, which has been erroneously the most adopted strategy).

Ciénega de Progreso, Yucatán 2015



Ciénega de Progreso, Yucatán 2018



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Responsibility:

This guide puts forward a strategy for implementing ecological restoration projects addressing mangroves, regardless of the extent of the impact or the climate, geomorphology, and hydrological conditions where they occur. Considerations are made for an inclusive operation by incorporating practices that promote gender equality and respect for the traditions and culture of indigenous peoples. The ideas and methods presented in this document are based on the best information available and the experience of the authors. They provide scientific and technical information to support decision-making, especially for informing policies, projects, or strategies for climate change adaptation and mitigation. The points of view and opinions expressed in this publication are those of the authors and do not necessarily reflect those of their institutions.

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OBJECTIVE AND SCOPE

This guide aims to educate and strengthen the capacities of anyone interested in restoring mangrove areas. It seeks to support efforts ranging from the formulation of proposals to the planning, execution, and monitoring of mangrove restoration programs. The guide is intended to be useful for government agencies, civil organizations, the academic sector, businesses, and society at large. It builds upon the foundations of restoration ecology and follows the principles of ecological restoration (ER) stated by the Society for Ecological Restoration (SER) ^[1] by making a synthetic presentation of the basic concepts of ER and their application to mangrove restoration.

This guide provides a strategy for integrating the social, economic, and ecological components rather than specific methods ^[2,3,4]. The strategy is presented in an orderly and standardized manner for better understanding, comprising three main stages: planning, implementation, and evaluation. By using conceptual and technical bases as a reference framework, the strategy should be applicable to all types of mangroves and impact levels ^[1,2,3]. Such bases include species physiology, habitat characteristics, and population, community, ecosystem, and landscape concepts. ER of mangroves is a Nature-based Solution (NbS) that contributes to mitigation and adaptation to climate change. This guide aims to improve the efficiency of mangrove ER, strengthen efforts to meet the objectives of multilateral environmental agreements

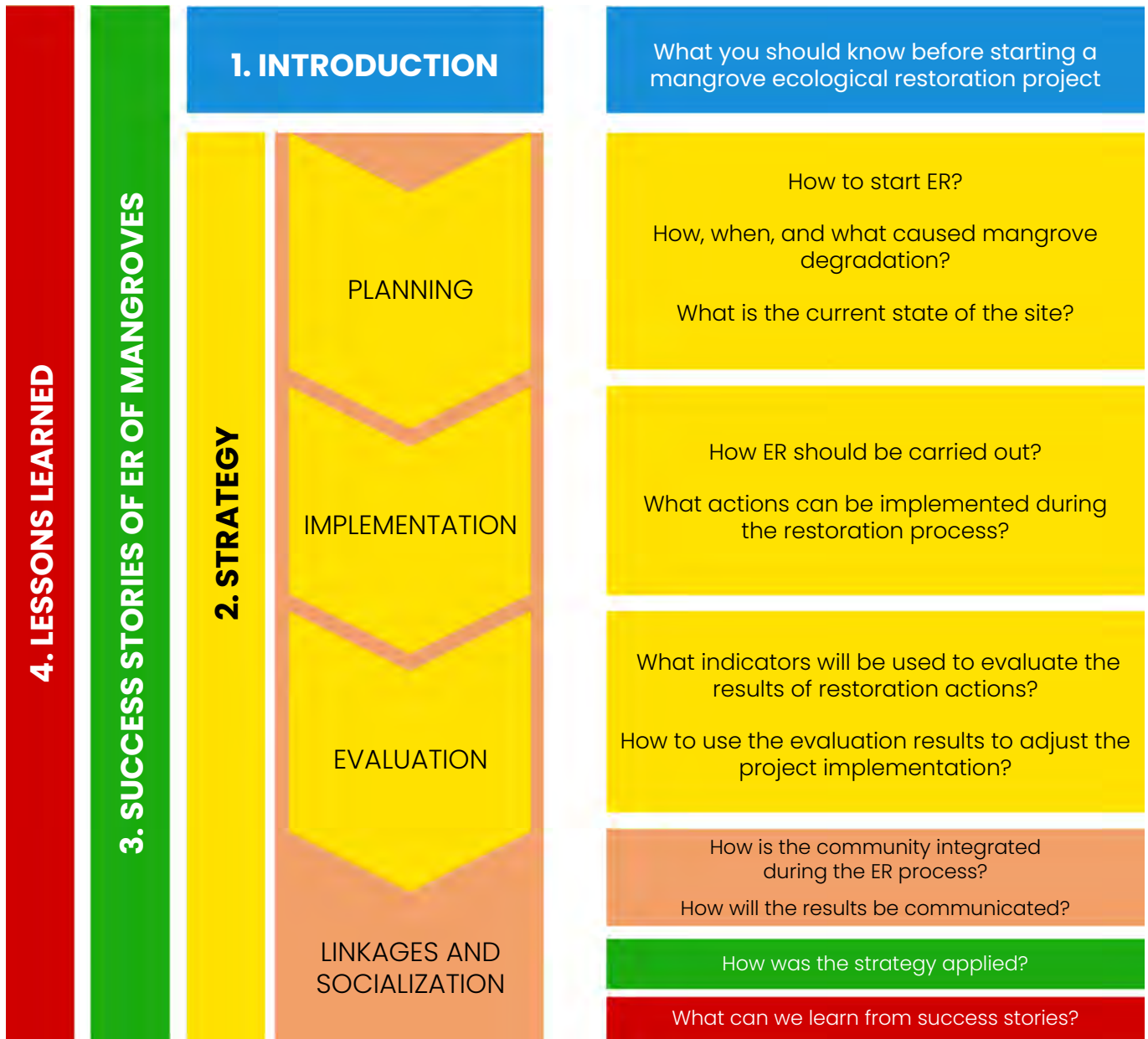
such as the Paris agreement to reduce greenhouse gas emissions, and contribute to attaining goals 13, 14, and 15 of the UN 2030 Agenda for Sustainable Development.

This guide is based on knowledge acquired and lessons learned, and the transfer of these to coastal communities. The strategy was developed as part of a research program carried out by CINVESTAV-IPN Unidad Mérida in collaboration with Universidad de Barcelona and Instituto Pirenaico de Ecología-CSIC (Spain), CICY and UNAM-Sisal (Mexico), Louisiana State University (USA), JICA (Japan), as well as Mexican government agencies (CONANP, CONAFOR, CONABIO, SEMARNAT-Yucatán, INECC) and non-governmental organizations (DUMAC, PRONATURA, Flora, Fauna y Cultura de México). The conceptual framework and general approach of the strategy have been published and implemented since 2007 in at least ten sites along the coasts of the Gulf of Mexico, the Caribbean, and the South Pacific ^[2,3,4,5,6,7].

HOW TO USE THIS GUIDE

The guide is structured in four sections. **1-** Introduction, sets the theoretical framework of ecological mangrove restoration; **2-** Strategy, develops the ecological restoration process in a systematic

manner comprising three stages: planning, implementation, and evaluation; **3-** Success stories, where three success stories are presented to illustrate the application of the strategy; and **4-** Lessons learned, highlighting key aspects to consider, based on results from projects implemented using the ecological restoration strategy.



1. INTRODUCTION

1.1 Mangroves

Why are mangroves important?

Mangroves are intertidal forest ecosystems adapted to a wide range of salinity and flooding conditions. They grow in 75% of the tropical and subtropical coasts worldwide and provide valuable ecosystem services (Figure 1) with a **global economic value estimated at 2.7 trillion dollars per year** [8]. Mangroves are among the most seriously threatened tropical ecosystems, mainly due to anthropogenic causes, such as the development of infrastructure for tourism and aquaculture activities, among others [9]. Although the loss

rate of mangrove forests has decreased from 2% to <0.4% in this century [10], projections indicate that 30–40% of coastal wetlands [11] and most mangrove forests could be lost within the next 100 years [12].

Ecological restoration of mangrove swamps is a Nature-based Solution (NbS) that allows addressing social challenges such as climate change mitigation, recovering services for human well-being, and conserving biodiversity [13]. **A comprehensive restoration strategy that integrates social, economic, ecological, and scientific-technical aspects is crucial for the successful recovery of mangrove swamps.** Missing one or more of these components has led numerous restoration projects to fail [14,15,16].

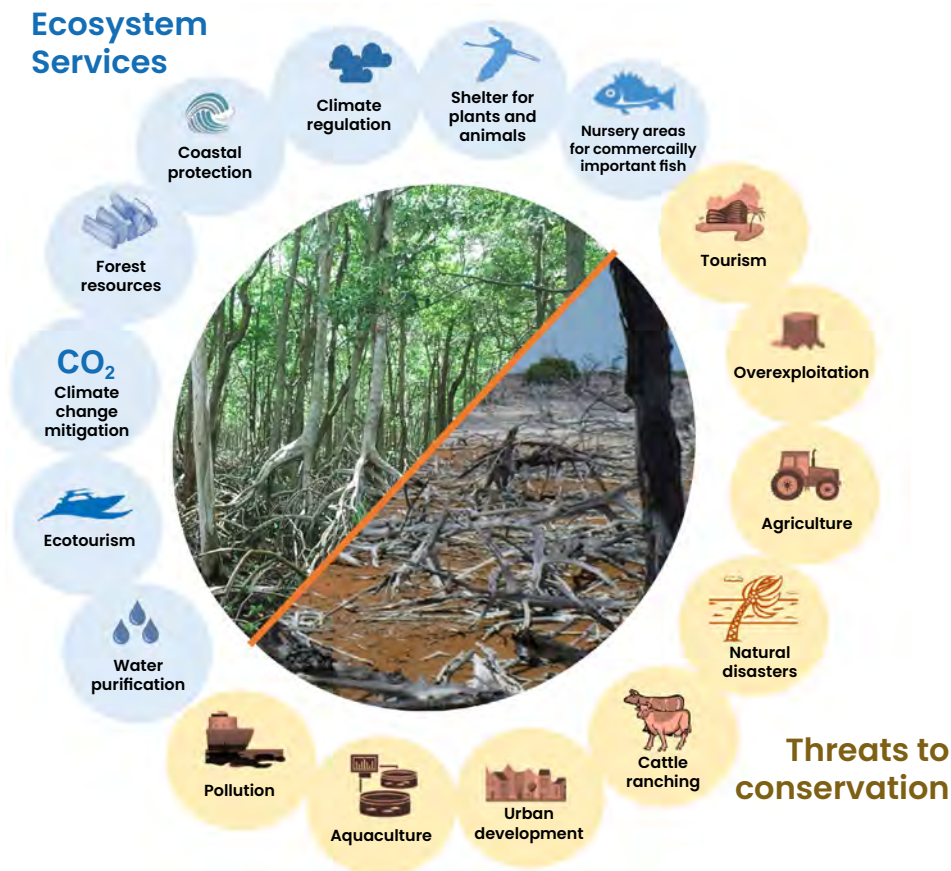


Figure 1. Ecosystem services provided by mangroves and threats to their conservation.

1.2 Basic concepts and principles

What should we know to start a restoration project?

Ecological restoration (ER) is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed so that it regains the values considered to be unique to the ecosystem and its capacity to supply goods and services to society^[1,17]. This approach requires integrating various disciplines across different scales^[18].

Restoration ecology is the multidisciplinary science that provides the scientific basis for restoration; it is also useful as an experimental test of ecological theories, that is, their application as a technology^[19] (Figure 2). From a methodological point of view, **restoration approaches can be classified into two types: passive restoration and active restoration**^[20].

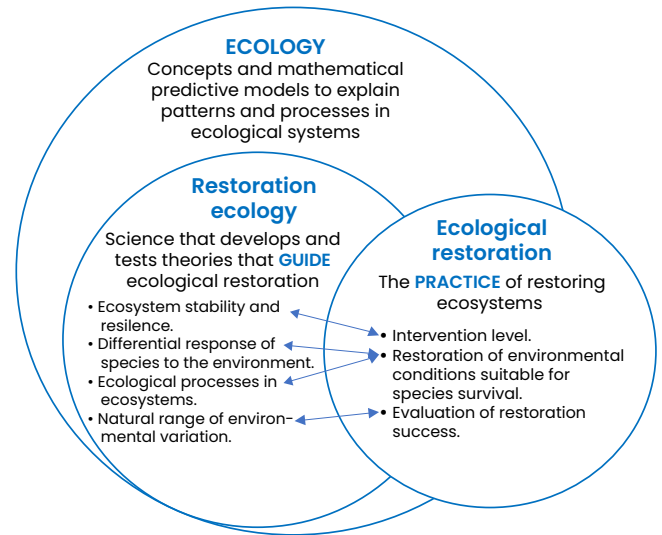


Figure 2. Relationship between ecology, restoration ecology, and ecological restoration. Modified from^[19].

Passive restoration

Eliminates disturbance factors (e.g., by channel rehabilitation) to favor natural regeneration.



Hydrological rehabilitation through the re-enabling of channels at Celestún, Yucatán.

Active restoration

Eliminates disturbance factors and implements actions to accelerate recovery (e.g., reforestation).



Reforestation in mangrove nurseries in Sisal, Yucatán.

Various **spatial and temporal scales** are involved in ecological restoration, from implementation to evaluation (Figure 3). Processes in ecosystems occur at different temporal (hours, days, years) and spatial (centimeters, hectares, region) scales and interact with the various levels of biological organization (individuals, populations, communities, ecosystems). Physiological processes occur at scales of hours and a few square meters,

reach up to the population level at scales of 1 – 1000 km² over time periods of 1 to 2 years; and reach up the landscape level, at scales of several thousand km², at least a decade after the start of the restoration [16,21]. Studying restoration at different scales allows identifying the outcomes of restoration actions, helps to answer various questions to better understand the mangrove restoring process and properly evaluate its success, or lack of.

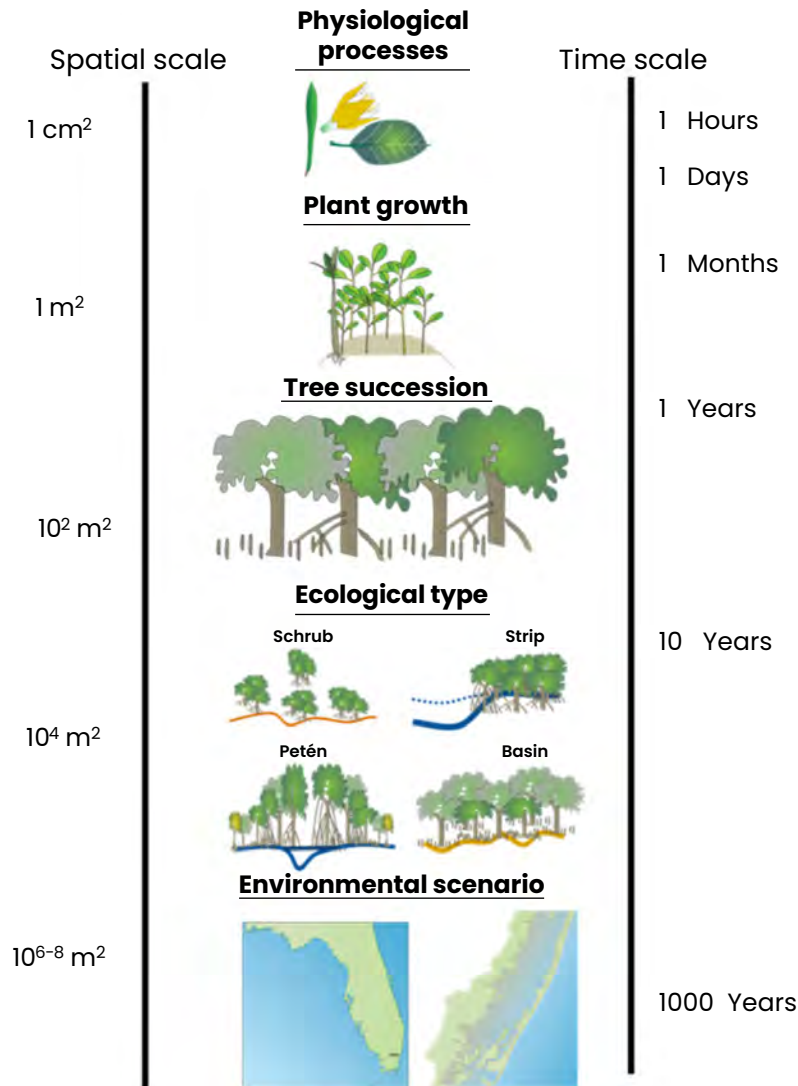


Figure 3. Spatial and temporal scales involved in mangrove restoration. Modified from [21].

Integrating the various social, economic, and ecological components is crucial for a successful restoration project [22]. The integration of these components provides a process based on ecological theory, which supports and makes restoration actions more likely to succeed by being economically viable – ensuring their economic sustainability throughout the project – and by pursuing social welfare, making them socially acceptable (Figure 4). The perception and participation of the local community are crucial to ensure the long-term continuity of the project

through the conservation and maintenance of the actions implemented and their outcomes on the site. An ER project should aim for social integration from the beginning, considering the local uses and customs, land ownership, site knowledge, and current management of natural resources. The ER project should also aim at increasing the awareness and valuation of mangrove ecosystems through environmental education actions, capacity building to diversify economic activities, and, in some cases, promotion of active participation in restoration actions.

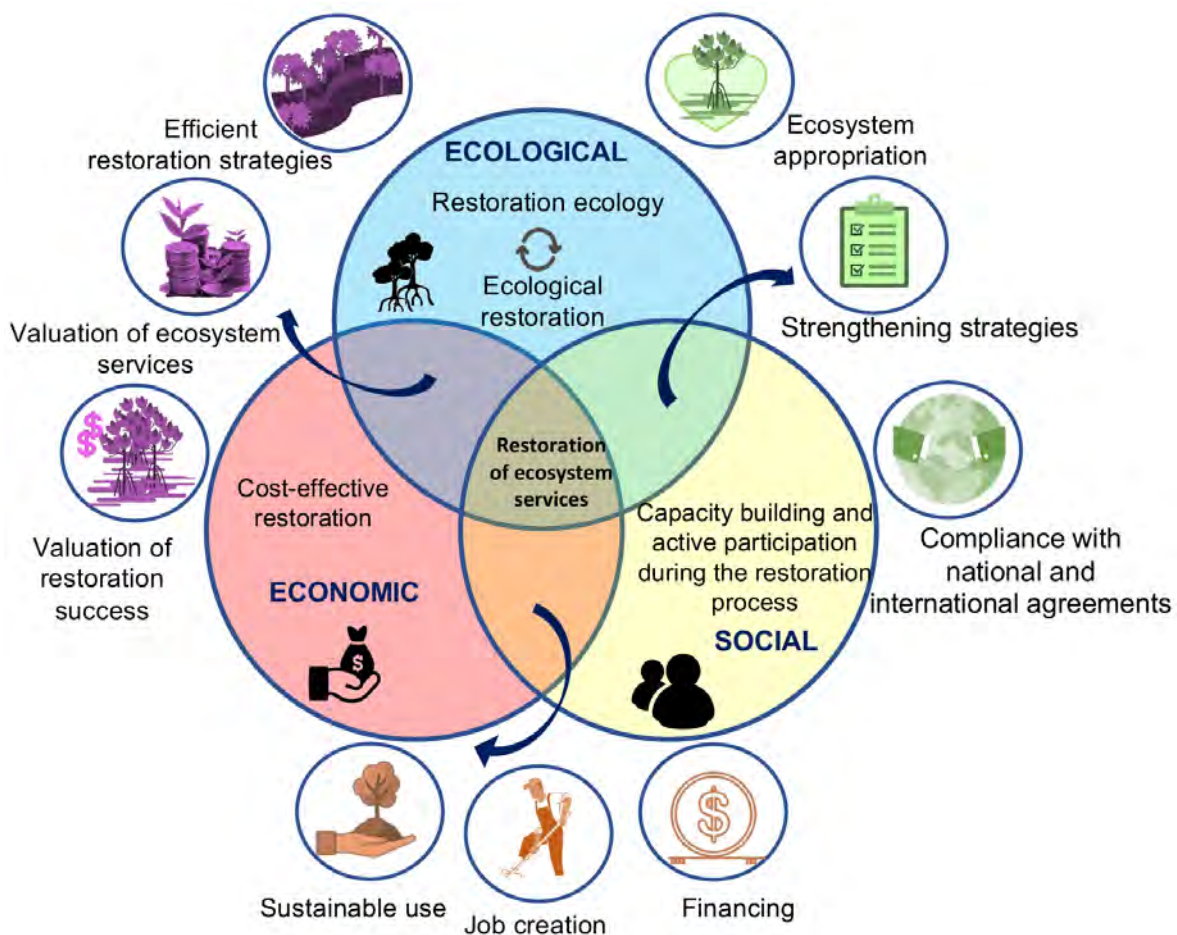


Figure 4. Importance of integrating ecological, social, and economic components throughout the ecological restoration process.

1.3 Ecological Restoration of Mangroves

How is ecological restoration carried out in the world?

Mangrove restoration has become a growing global effort. To date, the largest number of mangrove ER projects has been implemented in Asia, followed by America ^[16]. Reforestation has been the predominant strategy utilized in those projects; however, many of them have ended in failure at a substantial economic cost, mainly because they were implemented without incorporating the necessary ecological foundations ^[15,23,24]. ER of mangroves requires a prior assessment of on-site conditions. Also, restoration actions are selected considering the autecology of species; such actions usually include hydrological rehabilitation to favor natural regeneration or reforestation if these are identified as necessary according to the initial assessment of the system ^[4,24]. Based on experiences obtained from mangrove ER projects, key theoretical aspects for implementation and methodological manuals that provide useful field tools have been published ^[24,25]. This guide aims to continue strengthening the strategies currently available through a learning and evaluation process, as well as achieving the overall objectives and goals. ER should always be carried out following an adaptive management approach as this allows dealing with the uncertainties and complexity of the ecosystem and, based on the information provided by the program monitoring, promptly identify unsuccessful actions, and adjust the implementation accordingly to improve the results ^[41].

How much does restoration cost?

The cost of mangrove restoration varies widely across the world (figures in US dollars per hectare): \$3,000–510,000 ^[26], \$225–216,000 ^[27], \$1,000–100,000, ^[28] and \$40–176,000 in America, and \$1,000–67,670 in Asia ^[16]. The wide variability of restoration costs is related to the techniques used, cost of materials and labor, site accessibility, training workshops, and monitoring, among other factors ^[16, 26]. Mangrove recovery based on ER principles is estimated to yield a better cost:benefit ratio than techniques based on trial and error ^[27]. Compared to reforestation, the cost of ER through rehabilitation of hydrological flows to favor natural regeneration is not directly related to the size of the area to be restored. It is more cost-effective as it reduces the investment in dispersal centers for seedling production and the cost of planting works (Table 1). Reforestation has the additional shortcoming of establishing monospecific stands, making the ecosystem less resilient to impacts, disease, and invasion by exotic species.

Table 1. Average cost of mangrove restoration in America.

| | Reforestation (USD ha ⁻¹) | Hydrological restoration (USD ha ⁻¹) |
|---------|--|--|
| Average | 29,000 | 12,000 |
| Minimum | 162 | 147 |
| Maximum | 470,000 | 176,000 |

The cost of workshops and monitoring was not included in all the cases.

2. STRATEGY

The strategy for a successful mangrove ecological restoration project is based on understanding the ecology of this ecosystem, that is, knowing the interplay between geomorphology, hydrology, and the structural and functional characteristics of the mangrove ecosystem at different spatial and temporal scales [21,29]. The participation and representation of all sectors involved must be ensured throughout the restoration process, including local communities (social component), a scientific-technical group (academia), economic players and regulatory (e.g., government and local authorities), and funding stakeholders (Figure 4). Setting institutional arrangements and agreements based on the interaction of all sectors strengthens the governance of the group as these provide certainty to the actions and responsibilities of each party during the restoration process, thus ensuring its sustainability and the long-term permanence of the restored ecosystem.

The strategy focuses on planning restoration actions specific to each site according to the local and regional conditions. The strategy also includes a set of common components: a) convening a technical workgroup and delimiting the site to be restored; b) conducting a diagnosis and “forensic ecology” analysis of the site; c) formulating the restoration plan and actions; d) monitoring the progress and success of restoration actions; and e) establishing linkages and socialization. All the above must be accomplished within a framework of management instruments and in compliance with the institutional arrangements made between the stakeholders to ensure the restoration system self-sustainability in the long term (Figure 5). The linkages and communication of the lessons learned from each project help to strengthen the techniques implemented and strengthen the restoration strategy [2]. These components are divided into three stages: planning, implementation, and evaluation of the restoration program.

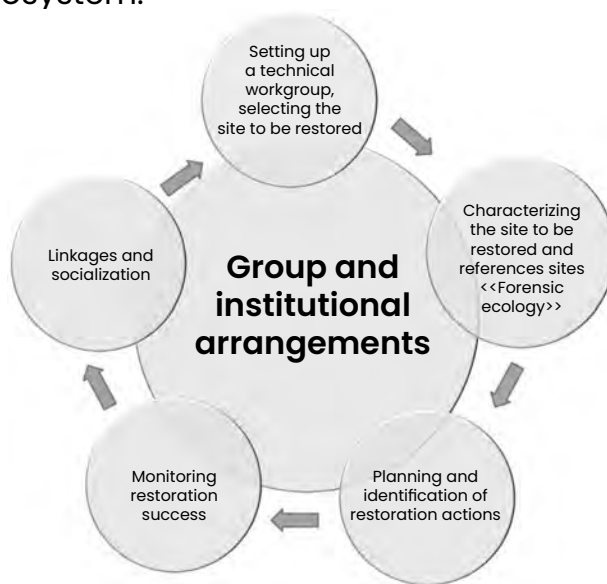


Figure 5. Strategy for the restoration of mangrove ecosystems [2].

2.1 Planning

Careful planning is essential for a successful ecological restoration project. Planning comprises:

2.1.1 Setting up a technical workgroup

The workgroup should include, to the extent possible, stakeholders such as **scientists, members of the local community, organized social groups, environmental managers, and representatives of funding entities**. Each sector — academia, society, authorities, and funders — participates and works in particular functions that promote the integrated development of ER (Figure 6). However, it is not always possible for all the actors in-

involved to participate from the beginning of the project. Their participation can be promoted during the restoration process through workshops, training events, and suitable advertising of the project, highlighting its benefits for each sector (Figure 4). For the various stages of the restoration process to take place and for the project to be sustainable over time, **arrangements among the project participants should be formalized to ensure proper coordination during the project execution** (Figure 6). The obligations and participation level of each group member should be defined from the beginning so that they all comply with the institutional arrangements and agreements throughout the restoration process, thus favoring its success and viability.

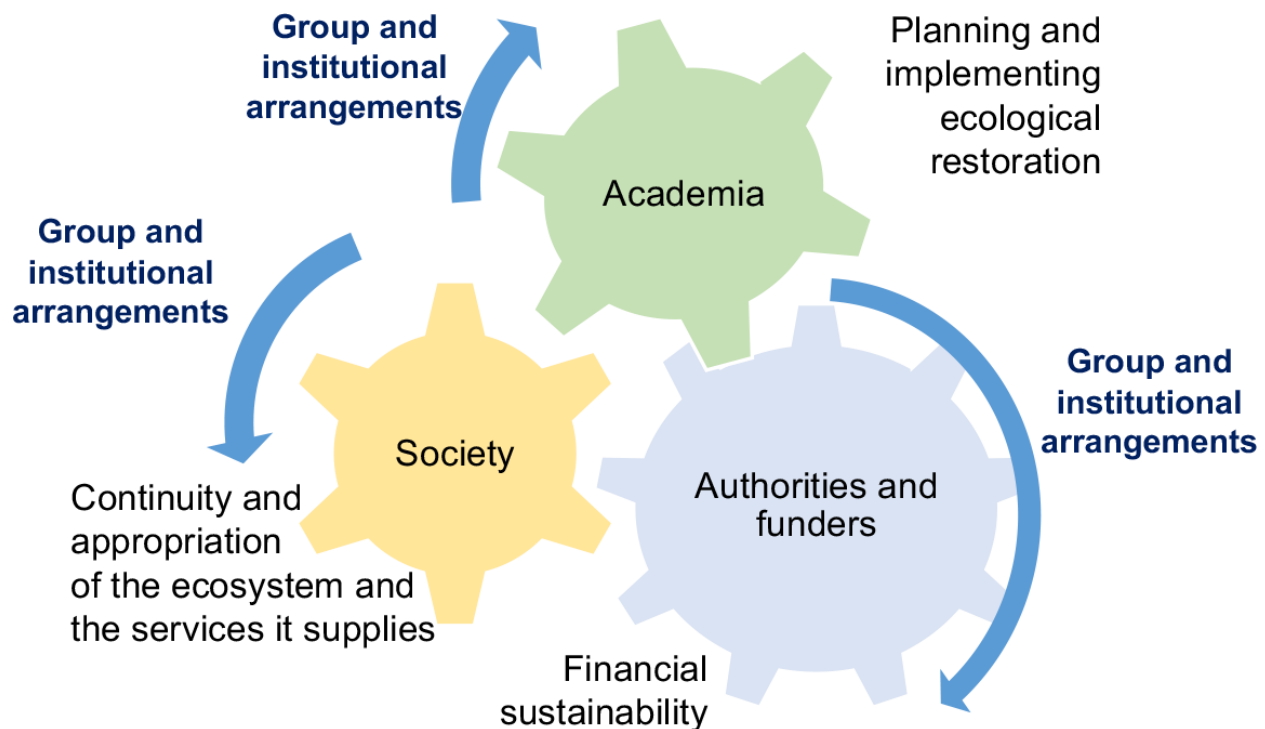


Figure 6. Social components of the workgroup.

2.1.2 Delimiting the site and setting objectives and goals

The selection of the site to be restored is key for the success or failure of a project. Some of the criteria that can be used for selecting the site are shown in figure 7. The mangrove potential restoration map available at <http://oceanwealth.org/mangrove-restoration/> provides a useful tool for selecting and prioritizing sites to be restored based on their potential provision of ecosystem services and other features ^[9]. Once the site has been selected, realistic and achievable goals and objectives should be set. The workgroup should clearly define *what the project aims to recover (ecological processes, vegetation structure, vegetation cover, landscape, etc.)*, *the rationale for restoring it (make a profit, solve a problem, etc.)*, *where and when to restore it, who will execute and coordinate the actions, etc.* Short-, medium-, and long-term goals and objectives should be set, and the restoration process should be subdivided into stages to allow evaluating the performance of restoration actions at each stage. Goals should be set in quantifiable terms, for example, a 50% reduction in interstitial salinity after one year (See success story 3.1).



Figure 7. Criteria for selecting the site to be restored.

2.1.3 Site characterization

Prior to starting the restoration, the causes of ecosystem degradation should be identified, and a diagnosis of the current conditions of the site should be made – this step is also known as “forensic ecology analysis” [2]. To this end, the site to be restored, a well-preserved or good-condition reference site, and a degraded or poor-condition site (preferably located near the site to be restored) should all be characterized. The well-pre-

served reference site depicts the target state to achieve after restoration. When a suitable reference site is not available, restoration objectives can be set based on other mangroves with comparable geomorphological and hydrological conditions, as well as on historical references. A novel approach for planning large-scale spatial and landscape restoration is to base it on community needs, combined with a vision to restore ecosystem services and function, as a nature-based (NbS) solution [30,31].

A forensic ecology analysis identifies the local and landscape-level causes that led to the death or degradation of the mangrove

Table 2. Variables to be measured in the characterization of the site prior to restoration.

| | |
|--|---|
| Topography | Topographic level (higher and lower elevation areas) |
| Hydrology | Hydroperiod (level, duration, and frequency) Water source (marine, freshwater) |
| Physical-chemical characteristics of (surface and interstitial) water | Salinity, redox potential, temperature, inorganic nutrients (nitrates + nitrites, ammonia, phosphates and silicates, sulfides) |
| Physical-chemical characteristics of sediments | Bulk density, organic matter, total nitrogen, total phosphorus, total carbon |
| Vegetation | Species composition, density, height, diameter, basal area, importance value index, potential regeneration (density and height of seedlings and saplings), density and height of pneumatophores |

The forensic ecology analysis begins by evaluating (at all the relevant scales) the geomorphological and hydrological characteristics, previous restoration projects (if any), and anthropic or natural (e.g., hurricanes) impacts, as well as the social context and institutions that have jurisdiction or influence over the site. An overview of the landscape, water sources, ways of access, etc., of the site is also necessary; freely available tools such as Google Maps can be used for this purpose. The information thus collected will help to identify specific restoration actions suitable for each site. The variables measured during the characterization stage will also serve as indicators of the route of mangrove recovery compared to the reference sites. Table 2 shows a recommended list of variables to evaluate at both the reference sites and the site to be restored.

The site characterization involves arduous field, laboratory, and cabinet work (Figure 8). Therefore, human and financial resources, as well as the time necessary for characterization, should be carefully considered. The season of the year when the characterization is to be carried out should also be taken into account as environmental conditions change throughout the year. For more details and alternatives



Two reference sites: A) well-preserved (good-condition) site; and B) degraded (poor-condition) site (Celestún, Yucatán, 2014).

for characterization techniques, the reader is referred to the CONABIO handbook ^[32] and the field manual for rehabilitators ^[20].

Considerations for site characterization

- Permanent sampling plots should be established and used during characterization, implementation, and post-restoration monitoring. Plots should be properly marked from the beginning of the project for proper follow-up.
- There should always be a suitable system for controlling, recording, and surveillance of the entire process of sampling, sample preservation, sample analysis, and data capture (chain of custody).
- Sampling should be carried out during the dry or low-flood season of the year to maximize work efficiency; interannual monitoring sampling should also be carried out during the dry season.

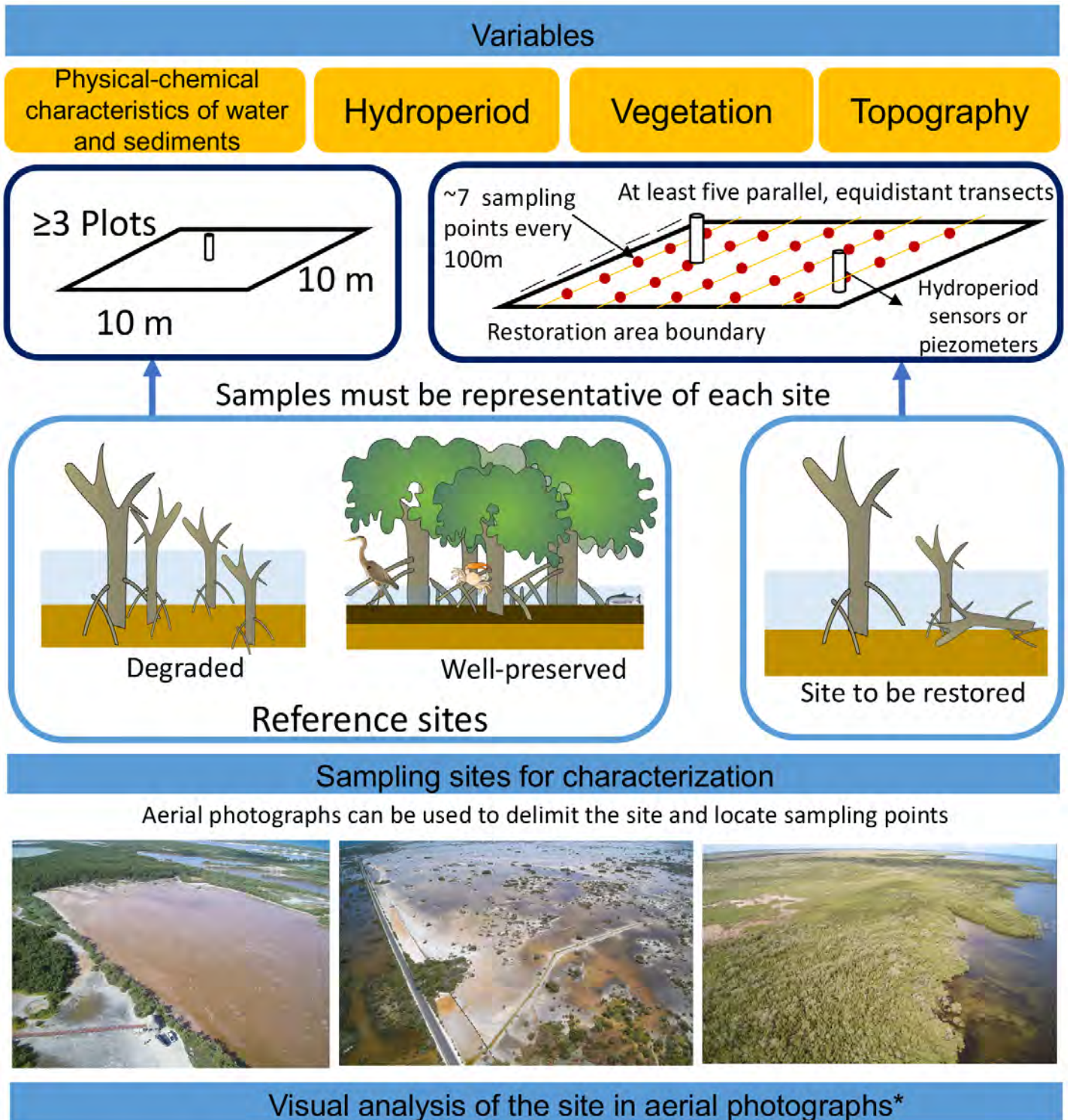


Figure 8. Example of a sampling design for site characterization for ecological restoration.
 *Google Maps® is a useful free tool to delimit the area to be restored, acquire maps of the site, locate key points (e.g., sampling points, water sources), etc.

2.1.3.1 Topography

Microtopography is useful to identify sites with higher/lower flood levels. This information is key for elucidating the causes of mangrove death or the lack of natural regeneration, as well as identifying site-specific restoration actions. Measurements should be made at both the disturbed and reference sites to have a topographic reference framework. Topographic characterization can be carried out as per the following steps:

Set transects equidistant from each other. Set sampling points along each transect; at least seven points over each 100 m linear segment are recommended to obtain a robust topographic model (Figure 8).



Topographic level is measured at the top-most level of the sediment layer at each sampling point using a differential GPS or with the water hose technique.



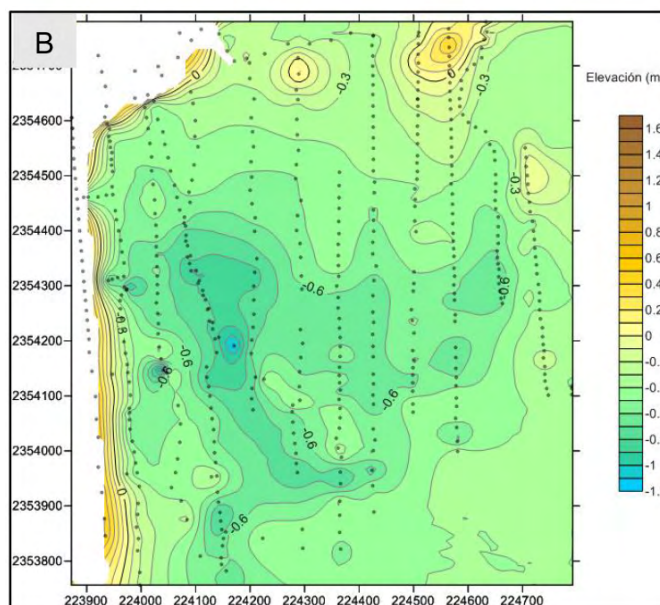
Obtain contour curves and construct a digital elevation model.



Identify accumulation and drainage zones (micro-basins), and directions of preferential flow.

Hydrodynamic models can be built when sufficient resources and data are available to construct bathymetry maps of the water bodies that influence the wetland. These allow a more efficient hydrological rehabilitation and a higher probability of success (See success story 3.3).

Microphotography and spatial and temporal variability of salinity and flooding are key variables that determine mangrove composition and structure.



A) Transects for topographic survey. B) Topographic elevation map for a locality in Progreso, Yucatán. Authors: Cecilia Enríquez and Ismael Mariño.

2.1.3.2 Hydrology

The hydrological dynamics or hydroperiod is determined by water level and frequency, and duration of floods. Hydrological dynamics regulates processes ranging from the growth of individual plants to the development of the biological community up to landscape aspects of the mangrove [33]. At the local level, hydroperiod controls variables such as salinity, nutrient availability in sediment, and the redox potential of the sediment.

Automatic pressure sensors can be used for measuring hydrological parameters. When sufficient sensors are available, they can be installed in elevated (fill) and low-lying (basin) areas. Sensors can be set to record data at regular time intervals (from minutes to hours) according to the variation in water level for up to 30–40 days for a first approximation. Afterward, sensors must be left in place for continuous recording to evaluate the progress and success of restoration actions. When automatic equipment is not available, piezometers can be installed,

and measurements carried out regularly (according to the frequency of water level variation and resources available). Figure 9 illustrates the installation of automatic pressure gauges; the process involves drilling a vertical hole into the sediment to insert the sensor. The sensor is a 3-inch diameter PVC pipe with perforations at the bottom, which are covered with mesh to prevent the entry of sediments.

The sources of water (i.e., fresh or seawater, surface, or groundwater) at the site are another key hydrological factor to consider. These must be represented on a map to understand their influence on the hydrology of the site and identify the presence of obstructions to the free flow of surface or subsurface water. This will assist in identifying the most suitable actions for the restoration plan.

The hydroperiod regulates many mangrove processes at different spatial and temporal scales.

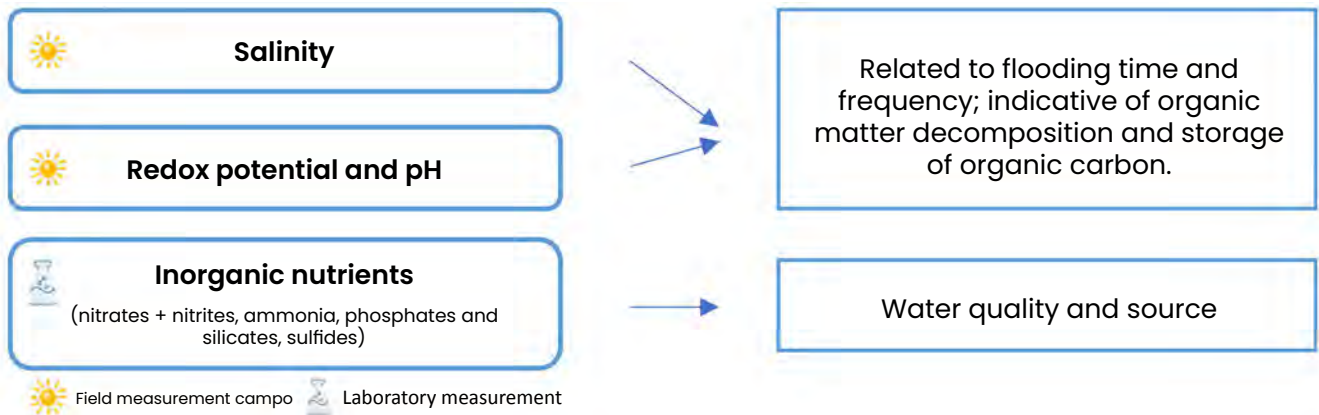


Figure 9. Installation of automatic pressure sensors at the reference and degraded sites.

2.1.3.3 Physical-chemical characteristics of water

The physical-chemical characteristics of interstitial water regulate the development, establishment, and structure of the mangrove swamp. Measuring these characteristics supports assessing the degree of disturbance of the site and setting a baseline against which progress, and success of the restoration actions can be assessed.

A 5-mm diameter Plexiglas tube connected to a hose fitted with a syringe at the end can be used for extracting interstitial water. The terminal end of the tube is open to be used as a siphon and is introduced approximately 40 cm deep into the sediment; an alternative is to install and fix a piezometer. The following measurements are recorded on the interstitial water sample:



Salinity can be measured with a refractometer or a multiparameter probe. Redox potential measures the flow of electrons during the organic matter oxidation-reduction process, and it can be measured with a field pH meter. Concentrations of inorganic nutrients dissolved in water are measured in a water sample collected in inert plastic bottles, which must be kept refrigerated until analysis in the laboratory. Analytical techniques are described in detail in ^[34] ^[35].




Measuring physical-chemical characteristics of water. A) Collecting a sample of interstitial water. Measuring interstitial salinity with B) refractometer and C) multiparametric probe. D) Measuring redox potential and pH with a field pH-meter, and E) measuring redox potential with copper rods, a voltmeter and a platinum electrode.

2.1.3.4 Physical-chemical characteristics of sediment

The physical-chemical characteristics of sediment are helpful to integrate information on the hydrological, geological, and biological conditions that determine the ecological characteristics of mangroves. These characteristics are also related to the fertility of sediment and are useful for determining whether the sediment is suitable for the successful establishment of seedlings. The number of sed-

iment cores to be collected will depend on the extension of the site; a minimum of three sediment cores per site (good-condition reference site, poor-condition reference site, and the site to be restored, plus the replicates of each) are required. Sediment cores are collected using a 50-cm long, 5.5-cm diameter metal or PVC tube. The samples collected are placed in plastic bags that are sealed and must be kept refrigerated until analysis in the laboratory. The analyses to be carried out are as follows:



 Field observations:
Color, organic matter, thickness



Laboratory analyses:

- Bulk density
- Organic matter content
- Carbon, nitrogen, and total phosphorus content



Collecting sediment cores with A) PVC tube, and B) metal tube.

2.1.3.5 Vegetation

The structure of the plant community must be evaluated in the good- and poor-condition reference sites, as well as in the site to be restored. At least three 10 × 10 m plots must be established at the reference sites to characterize the vegetation of each mangrove type present in the area. Plots at the site to be restored will be established only at points where vegetation (dead trunks or trunks) still remains. If only small patches of vegetation exist therein, these will be sampled as they are

found at each sampling point. The suggested structural attributes to be recorded in mangrove studies ^[36] and the potential regeneration (density and height of seedlings and saplings) will be measured in all plots. Figure 10 illustrates these attributes.

The vegetation structure of the good-condition reference site indicates which species grow naturally, as well as the age and maturity of the site prior to disturbance.

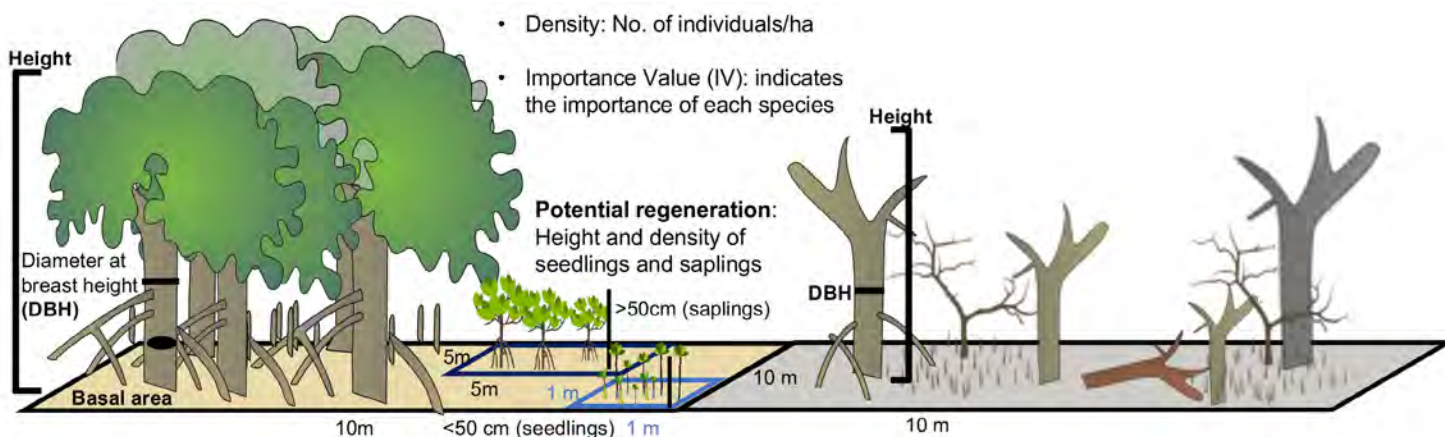


Figure 10. Structural attributes of vegetation at the good-condition reference site and the site to be restored.

Given the extension and usually difficult access conditions of mangroves, conducting an exhaustive in-situ assessment is not always feasible. Remote sensing is a tool that helps to conduct spatial analyses based on the detection and quantitative evaluation of landscape units, as well as differentiating dominant territorial units and the main factors associated with them at the landscape level. In-situ

vegetation structure measurements coupled with remote sensing tools improve the accuracy to identify the agents involved in the processes that define spatial units. Unmanned aerial vehicles (drones) are also a valuable tool for gathering information during the characterization stage, as well as for tracking the progress of the restoration process.

2.2 Implementation

An action plan must be formulated before starting restoration actions. The plan should encompass both restoration and monitoring actions. The action plan specifies what, where, how, and when the actions will be carried out and the costs of each of them. Monitoring allows assessing whether the actions being implemented are successful or whether adjustments have to be made to achieve the goals and objectives set by the workgroup. Restoration actions are implemented through ecological engineering, i.e., construction methods specifically adapted to improve ecosystem functioning ^[37], such as al-

tering the microtopography, re-opening water channels to restore hydrological flows and allow the natural establishment of mangrove species. Applying actions based on ecological engineering reduces response and maintenance times.

Each restoration process should be a custom-tailored solution, a set of site-specific actions. Simply copying or reproducing actions from one location to another without proper analysis can lead to poor cost-efficiency actions and failure. Restoration actions should always be based on the information obtained during the site characterization stage.



Natural regeneration in dispersal centers in Sian ka'an, Quintana Roo, 2018.

2.2.1 Restoration actions

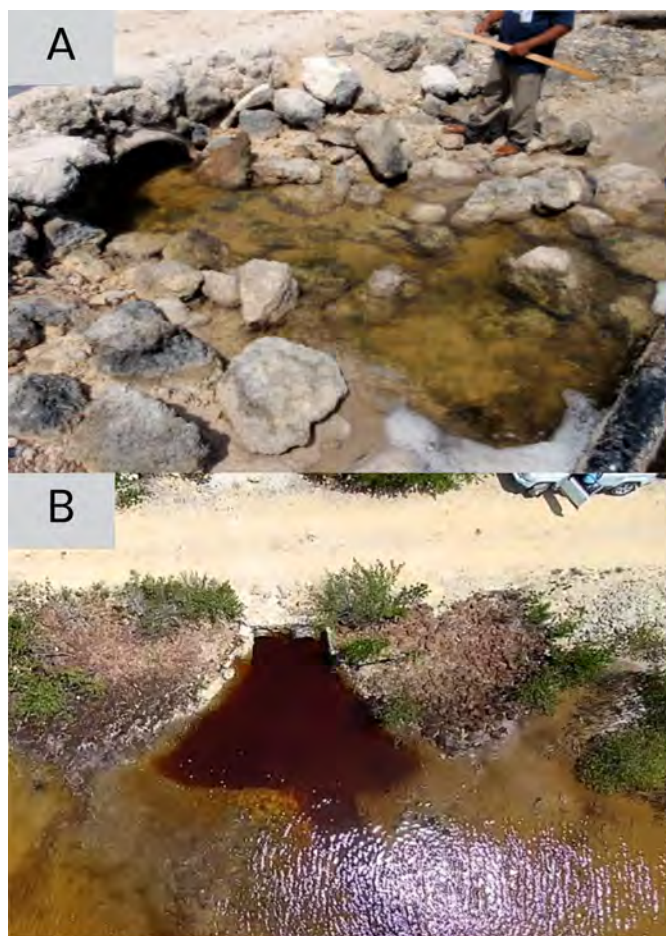
Restoration actions usually consist of works and activities carried out by specialized professionals or members of the local community, supervised by members of the technical group. Restoration actions are defined based on the characterization of both the site to be restored and the (good- and poor-condition) reference sites. Goals and implementation times must be set for the various restoration actions. [Activity logs, action verification reports, and photographic records must be kept as control mechanisms.](#) Participation of the local community in the implementation of restoration actions is strongly recommended as this allows the community to become actively involved in the project and better appreciate the value of the mangrove ecosystem and the outcomes of restoration. Participation of the local community should be comprehensive and considered as a long-term process. Those community members that, in addition to being proactive, also promote group formation and coordination should be identified, as they are called “community champions”. The restoration actions recommended by this strategy are described below. Other techniques are described in the field manual for rehabilitators ^[25].

2.2.1.1 Desilting water passages

Road construction is one of the main causes of hydrological changes in mangroves. Water passages usually designed in construction works are ineffective as they do not allow the free exchange of water. Therefore, [it is necessary to build channels – or alter the existing channels – to connect the wetland, or conserved area, with the disturbed mangrove area to](#)

[allow a free flow of water between them.](#)

Water passages should have an inverted “V” shape with the apex at the connection point and have a length of approximately 5 m. This shape facilitates the spread of the water passing through these structures to reach the broadest area possible. The depth of water passages should be duly considered to ensure that water can flow even at low tide and during the dry season of the year. These dimensions are intended to serve as a guideline only and should be adapted according to the specific water flow intensity and tidal variation in the area to be restored ([See success story 3.2](#)).



A) Water passage obstructed; B) Water passage de-silted in an inverted “V” shape to improve water distribution in Sian Ka’an, Quintana Roo.

2.2.1.2 Relocation of organic material

As a result of natural events, the impact of anthropic activities, and previous unsuccessful restoration actions, remains of dead vegetation and other debris may likely exist in the site to be restored. Such materials could limit or restrict the free flow of surface water through the desilted or rehabilitated channels and will have to be removed and relocated. The organic material removed should be relocated somewhere within the area being restored so that its decomposition process can continue and provide nutrients to the soil, but without obstructing water flow. **Organic materials and sediments can also be used to add topographic heterogeneity to the restoration site, as well as a backfill for low-lying areas.** A heterogeneous ecosystem favors repopulation by different species, which, in turn, facilitates secondary succession and provides greater resilience to impacts compared to homogeneous ecosystems such as monospecific reforestation.



Removing debris and organic matter from the restoration site.

2.2.1.3 Desilting natural tidal channels

This action can be started once the natural tidal channels of the site have been identified through the analysis of satellite images, photographs, prospecting and field sampling, or the topographic survey. The original channel paths can be traced on satellite images from Google Earth (See 3.2). The width and depth of these channels should mimic the natural configuration of each site in order to provide heterogeneity and mitigate the erosion of walls from ebb and flow of water, thus reducing the frequency of maintenance works.

Efforts should be made to follow the original zig-zag paths of channels to improve water circulation and reduce maintenance costs.



Desilting natural channels (Progreso, Yucatán).

2.2.1.4 Enabling new channels

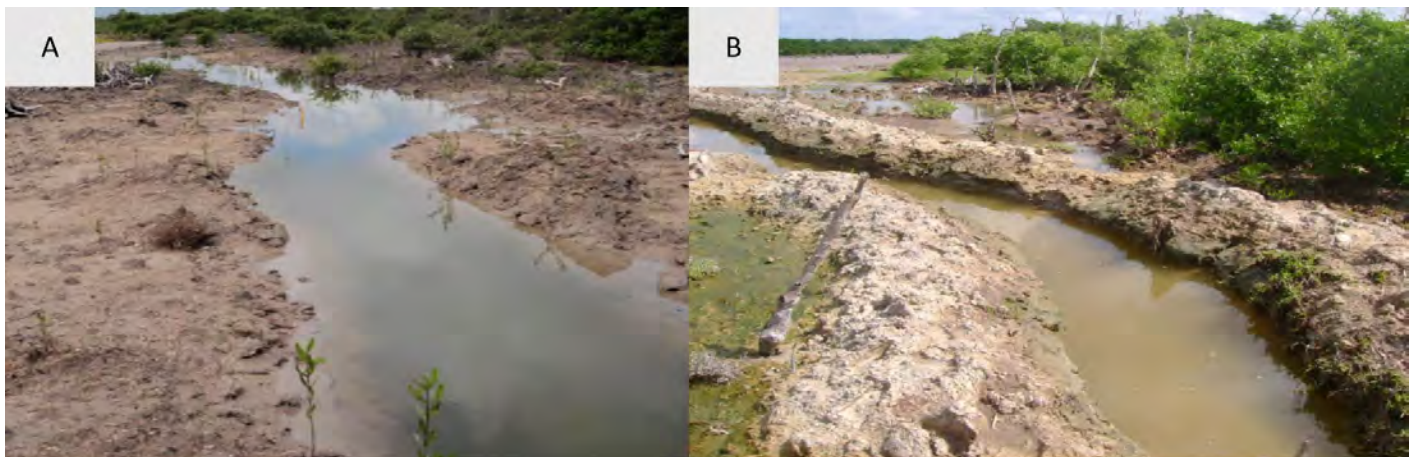
The topographic configuration in the restoration area might have likely changed as a result of disturbance and weather events. [Field trips, supported by examination of aerial images, topographic surveys, identification of water sources, and preferential-flow models, will help to identify the most suitable “routes” for constructing new channels](#) intended to increase the flow of water to the restoration area. Works for building these new channels should take into account

water exchange efficiency so that the water residence time is determined by both the tides and the freshwater runoff from the mainland. Ensuring the free circulation of water increases the chances that the new channels will work properly. When rehabilitating existing channels, it is recommended that they follow a zig-zag trajectory. Sediment removed during the construction or rehabilitation of channels must be raked towards the ends or used to fill up low-laying sites, if needed, or to construct dispersal centers.

The sediment piled up along the edges of constructed/rehabilitated channels should be leveled off to allow the free overflow of channel water.



Rehabilitated channels with zig-zag pattern.
Progreso, Yucatán.



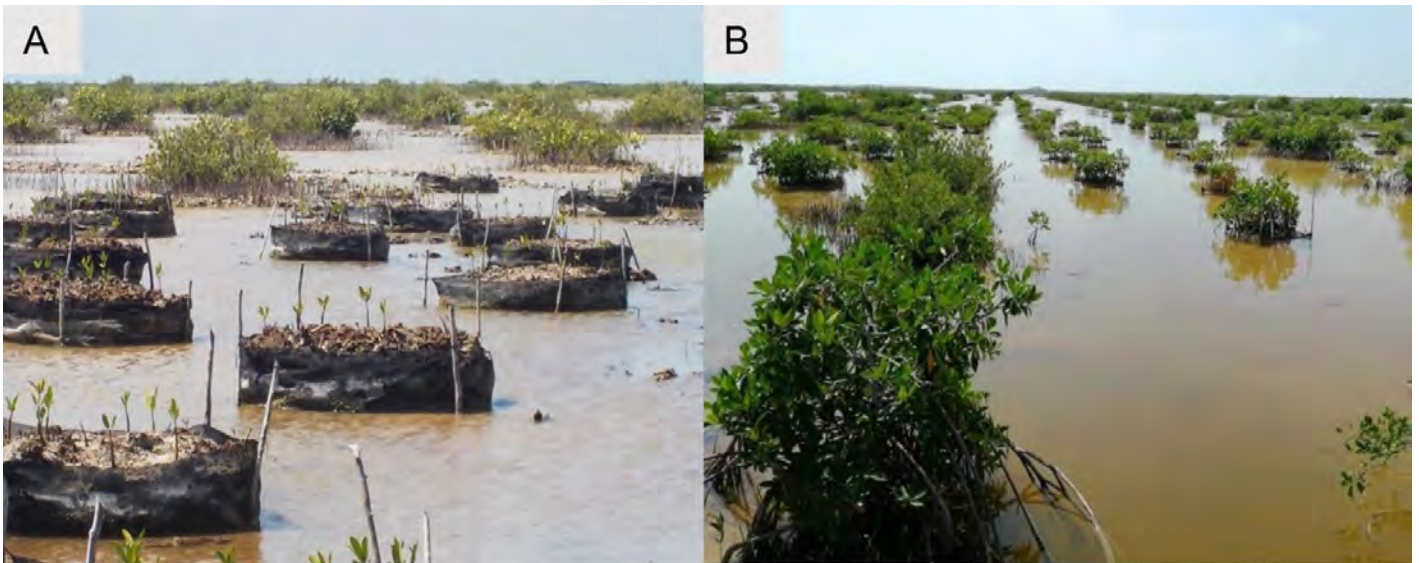
A) Channels with edges leveled off to allow water overflow to adjacent areas. B) Channels with sediments piled up along the edges as result of construction work. Progreso, Yucatan.

2.2.1.5 Conditioning dispersal centers

Dispersal centers (DC) are areas that have been delimited and topographically modified to raise up their level by accumulating sediment and form mounds that are stabilized using mesh or other materials. The main objective of DCs is to promote adequate flooding conditions for the successful establishment of seedlings. The implementation of DCs has yielded promising results — at a relatively low cost — when the goal is to induce natural regeneration over tens to hundreds

Dispersal centers possess hydrological and sediment conditions that are suitable for the successful establishment of seedlings.

of hectares ^[38]. DCs are recommended for areas where the flood level is higher than the average height of seedlings and propagules at the time of their establishment. Such heights can range from 0.3 to 0.6 m above sea level in sites with little tidal oscillation (<1 m), up to more than 1 m in sites with greater tidal oscillation or flood. Interstitial salinity can vary from <5 to 70 g/kg. The type of sediment will depend on the region, but it has to have good drainage; sediments with high silt or clay content can be mixed with 20%–30% sand to improve the drainage. These characteristics allow DCs to be more stable given their elevated position and maintain salinity conditions that are favorable for the establishment of seedlings. The height of DCs should be at least 5%–10% below the maximum flood height at the site to be restored. Information from the characterization of the reference sites is crucial to define these variables accurately.



A) Dispersal centers with reforestation; B) Dispersal centers with natural regeneration. Sian Ka'an, Quintana Roo.

The number, density, and location of dispersal centers should be decided based on the size and initial conditions of the area to be restored, considering the topography and preferential flows, as well as the availability of economic funds and cash flow. Dispersal centers should not all be the same height, as different heights add topographic heterogeneity (Figure 11) and create different flooding levels. In this way, the repopulation of mangrove seedlings takes place according to their

tolerance to flooding level, as occurs naturally in the ecosystem due to microtopographic variations. Dispersal centers can also function as reforestation centers that will contribute, through active restoration, to accelerate the recovery of vegetation structure (See 3.2). Any alternative should be decided in accordance with the institutional agreements and group arrangements and should be aligned with the objectives and goals that were set at the start of the restoration project.

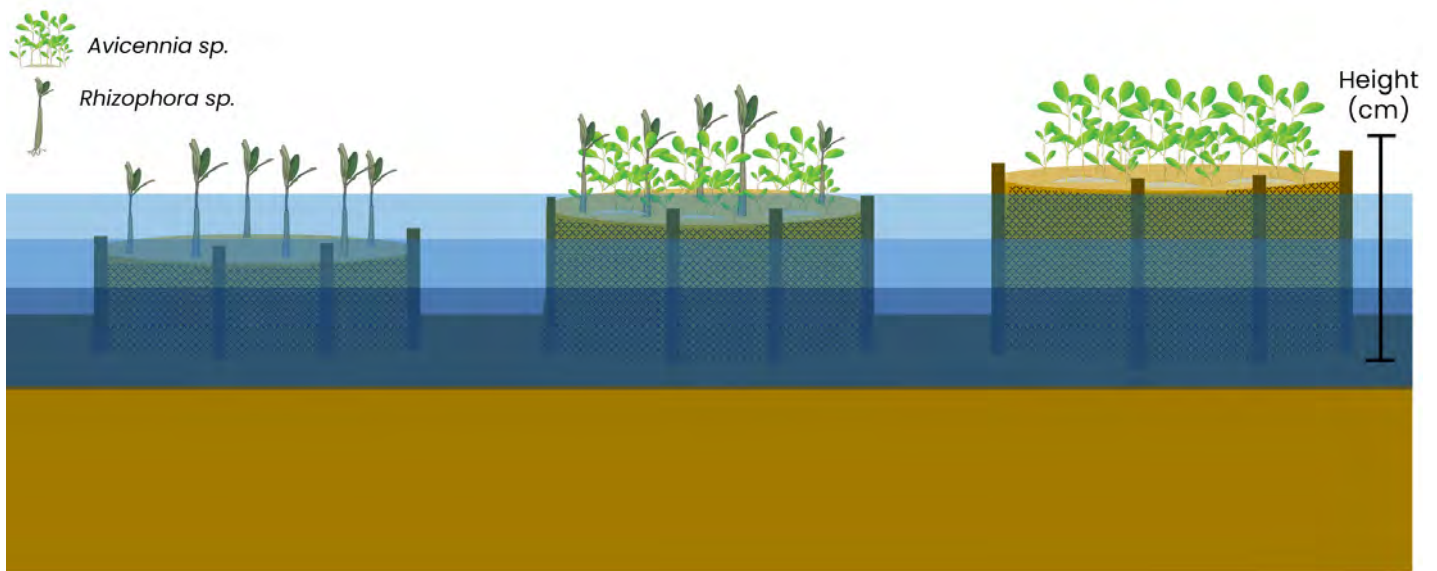


Figure. 11. Illustration of dispersion centers with different topographic levels to generate greater heterogeneity in the landscape.

2.2.1.6 Reforestation

Reforestation is the technique most widely used in mangrove restoration projects worldwide [16,23,39]. However, when reforestation is carried out without first analyzing the environmental conditions at the site to be restored, it may end up in failure at a considerable cost in terms of resources and effort. **Reforestation is recommended only when there is limited availability of propagules [24], provided the flooding and the physical-chemical conditions of water and sediments are suitable for the successful establishment of the seedlings sown.** When these conditions are not suitable, appropriate restoration actions should be carried out prior to planting. Reforestation can accelerate the recovery of the structure and functions of mangrove forests and can also serve as a strategy for furthering social involvement in the project. However, reforestation should be carried out only if the project objectives so require it. The following recommendations must be taken into account for implementing reforestation work:

- Plant materials to be used for reforestation should be collected from well-preserved areas surrounding the site to be restored (e.g., the good-condition

reference site), and the species should be selected considering the species composition in surrounding mangrove areas.

- Plant materials must be collected from non-contiguous points separated at least 20 m from each other to include greater genetic diversity and avoid collecting several propagules from a single parent plant or from close relatives.

- Propagules and seeds collected in the field can be kept in open-walled or permeable containers immersed in water, provided the water level does not flood or choke the biological material; propagules and seeds may be kept in bags, although these should preferably be maintained bagless.

Based on our experience, we do not recommend establishing nurseries. In addition to the construction and maintenance costs, they make the biological material to go from a “pampered” controlled environment to a physiologically demanding environment where it is exposed to varying light, temperature, and salinity conditions. The biological materials that survive in open-walled or permeable containers are more likely to survive under field conditions.



A) Conditioning the sediment for planting through citizen participation in Celestún, Yucatán.

B) Planting seedlings of red mangrove (*Rhizophora mangle*) in Chelem, Yucatán.

2.3 Evaluation

2.3.1 Monitoring restoration

Every restoration project should include a monitoring program to evaluate restoration actions. [Ecological restoration projects should be monitored for at least five years^{\[1\]}](#); however, restoration of wetlands may take a longer time (>10 years ^[40]). Monitoring starts by identifying specific variables (physiological, hydrological, vegetation structural characteristics, landscape, physical-chemical characteristics of sediment, diversity of organisms, and ecological or functional characteristics, among others (Table 2), that will function as indicators of the success of the restoration program. Those variables should be measured at both the site to be restored and the reference sites. Following the adaptive management approach ^[41], when the monitoring shows little success in achieving the goals set initially, changes in the type of actions being implemented might be required.

Since the variables being monitored have different response times (Figure 13), [their sampling frequency should be dictated by the nature of these variables, progress of the restoration, and \(human and material\) resources available](#). The sampling frequency must be every 3–6 months over the first year and at least once a year thereafter. Changes in the variables over time must be analyzed with respect to those at the reference sites to get an approximate indication of the trajectory and speed of recovery (functional curve) (Figure 12) ^[29].

Recommendations for monitoring

- The same sampling points established during the characterization stage should be used for restoration monitoring. Data gathered during the characterization stage describe the baseline conditions (time 0).
- Monitoring of vegetation at the restored site starts when seedlings appear; these are measured in 1 ´ 1 m plots. When seedlings grow into saplings, the plot size should be increased to 5 ´ 5 m. Larger (10 ´ 10 m) permanent plots are used when saplings develop into adult plants.
- When seedlings are measured at the site being restored, seedling recruitment, survival, and growth should also be measured at the reference sites.

As the success of a restoration project is observed at various spatial and temporal scales, indicators of short-, medium- and long-term success are necessary.

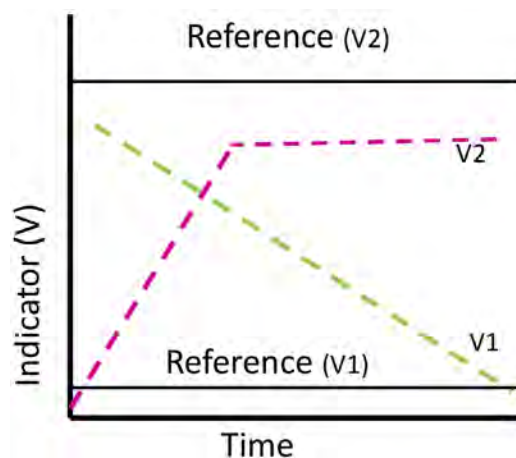


Figure 12. Example of monitoring of success indicator variables through operating curves in ecological restoration.

Indicators of success of ecological restoration

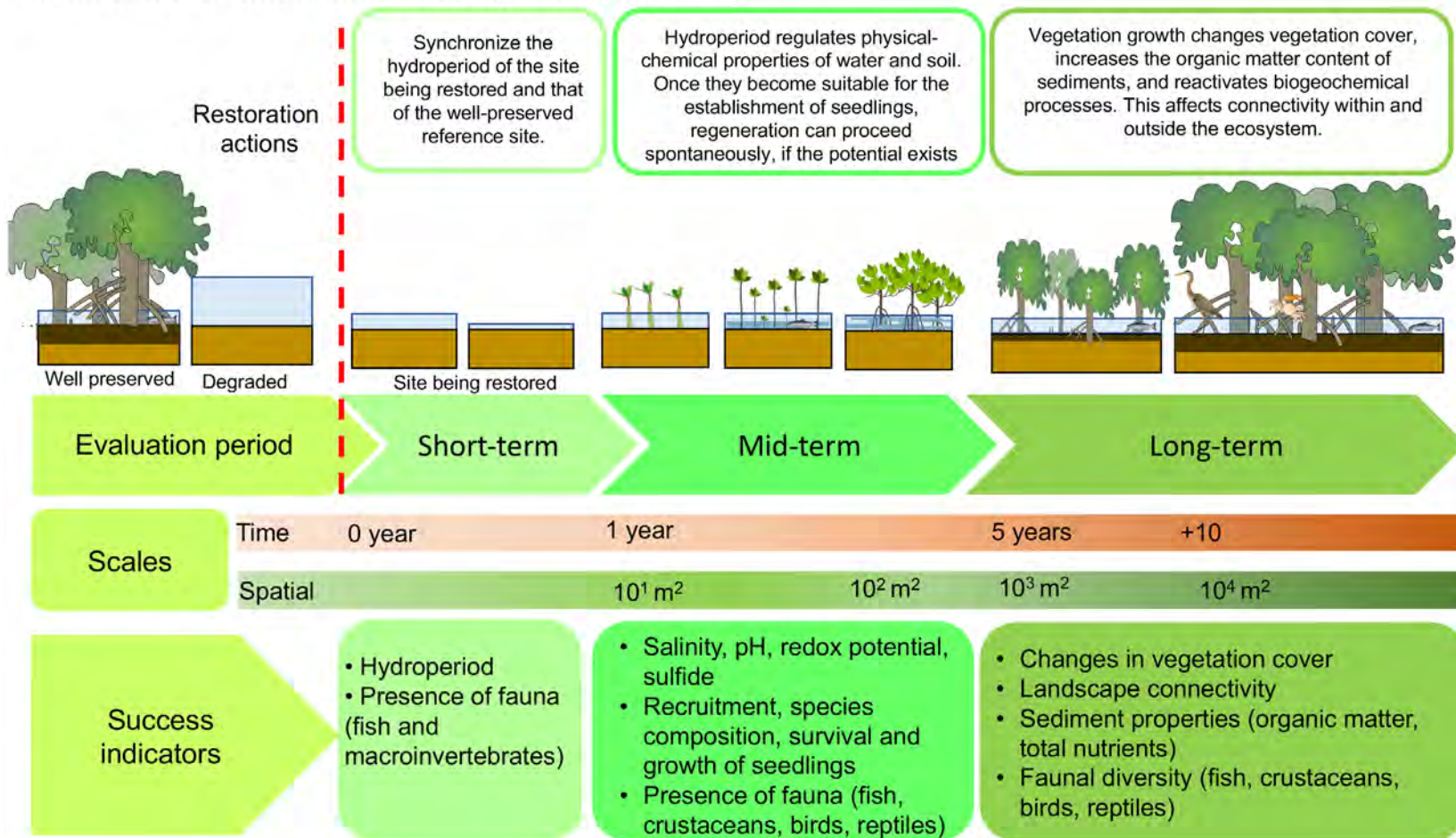


Figure 13. Simplified model for monitoring success indicators in mangrove ecological restoration in the short-, medium-, and long-term.

2.4 Linkages and Socialization

The social component is crucial for a successful ecological restoration project, and the local community should be included and participate in every stage of the project. **The project must be presented to and discussed with the local stakeholders –direct or indirect beneficiaries of the restoration, actors implementing the various actions, economic contributors, and local authorities.** Aspects worth highlighting are the support and guidance that should be provided to partici-

pants living in the area surrounding the impacted site. In principle, they should take ownership of the restoration project by effectively participating in its implementation, diversifying their activities to ensure that the results are sustainable in the long term (Figure 14). Participation of social science specialists in the project is recommended to allow a broader integration of society, promote the diversification of activities for the sustainable use of the mangrove ecosystem through workshops and capacity-building activities, and evaluate the social impact of the project.



Figure 14. Participation of local citizens during the ecological restoration process.

It is in this context that RE becomes an action of ecosystem-based adaptation, as it also seeks to obtain benefits for society. This means modifying the interaction between the socioeconomic and ecological systems in such a way that both are benefitted.

The experiences obtained from each project are a valuable source of information. **Both successful experiences and those that did not yield the expected results should be reported.** Other projects could leverage this feedback and learnings to avoid making the same mistakes and, ideally, replicate (with suitable local

adaptations) methods that have proved to be successful. Communicating the project results is crucial for improving the current restoration strategies. The results can be shared through research documents, social networks, formal and informal capacity-building activities, community-based monitoring, organized groups coordinated by the technical group, etc. The communication and outreach component of the project increases the likelihood that the restored site becomes part of the environmental assets or natural capital of the local community.



Different formal and informal socialization mechanisms of the mangrove ecological restoration process, and presentation of results.

3. SUCCESS STORIES

3.1 Celestún

Workgroup:

CINVESTAV-IPN Unidad Mérida, Ducks Unlimited de México, A. C. (DUMAC) and the Comisión Nacional de Áreas Naturales Protegidas (CONANP); with funds

from Comisión Nacional Forestal (CONAFOR) and the Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO), *Manglares de Dzinitun* association.

Area restored: 112 ha



Celestún, Yucatán, prior to restoration.

| Objective | Goals | Criteria | Indicator | Variables |
|---|--|---|--------------------------------------|--|
| Restore the ecological conditions of the mangrove through actions that make it self-sustainable | Synchronize variations in water level between the channel built and the mangrove being restored. | Hydrological connectivity. | Hydrology. | Frequency, level, and duration of inundation. |
| | Reduce interstitial salinity by 50% | Physical-chemical characteristics of water. | Salinity reduction. | Salinity of interstitial and surface water. |
| | Promote natural regeneration within an 18-month period. | Natural recruitment and vegetation structure. | Establishment, survival, and growth. | Seedling density, species composition, height, and diameter. |

Diagnosis:

The deterioration of this mangrove area was caused by the construction of a new main road to the Celestún town. The road interrupted the flow of surface water, leading to increased interstitial salinity (>100 g/kg) for long periods, whereas the average value at the good-condition reference site is 61 g/kg. In addition, the soil was in reduced condition due to prolonged flooding.

Restoration actions

The main restoration action was the construction of a 1,576 m long, 3 m wide, and 0.8–1 m deep channel to connect the adjacent lagoon with the impacted mangrove area in order to rehabilitate its hydrology (hydroperiod). The local community and civil society groups participated actively in the definition and execution of these actions.

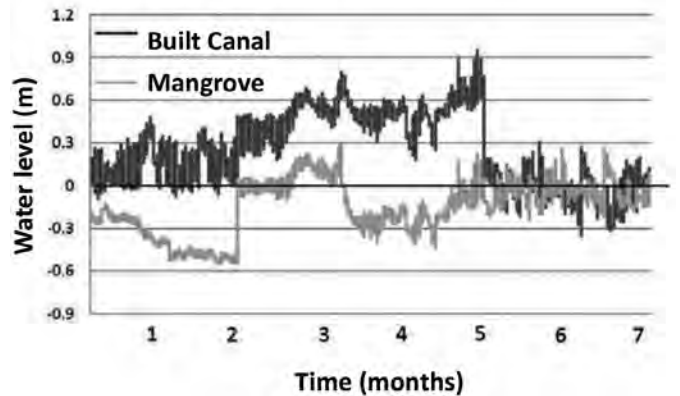


Figure 3.1.1. Flooding level synchronization after restoration. The zero value indicates the sediment height level [2].



A) Construction of the main channel;
B) main channel one year after the restoration actions started.

Evaluation

Salinity gradually decreased to an average of 45.2 g/kg (Figure 3.1.2 A). After the hydrological rehabilitation actions, *Batis maritima* and *Salicornia virginica*, species that function as “facilitators”, established spontaneously in the site, colonizing bare soil, reducing interstitial salinity, increasing nutrient concentration, and retaining mangrove propagules [42]. The three mangrove species also established spontaneously in the site (Figure 3.1.2 B, C). Five years after restoration, plant cover had increased by 60% and the dominant species were *Rhizophora mangle* and *Laguncularia racemosa* [16]. The mangrove community began gradually recovering its functions, as indicated, for example, by fish that repopulated the mangrove area under restoration as a breeding and feeding area [43].

During the restoration process, awareness-raising and capacity-building workshops were delivered to the community. As a result, the residents who participated in constructing the channel subsequently created a civil society (*Manglares de Dzinitún*) to provide community-based ecotourism services with various activities at the restored sites. This ensured the long-term conservation of the restored site and contributed to divulge the results of the project [2].

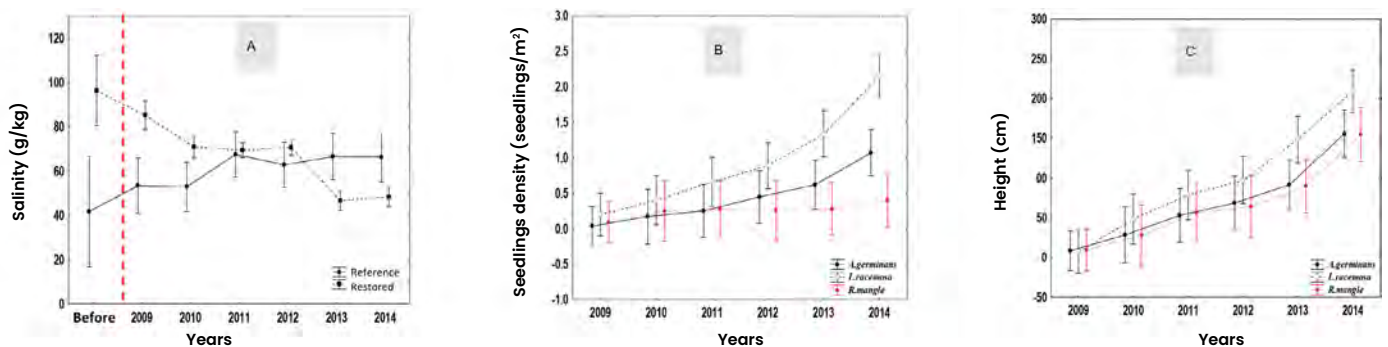


Figure. 3.1.2. Monitoring of A) salinity; B) natural recruitment; C) seedlings growth at the restoration site.



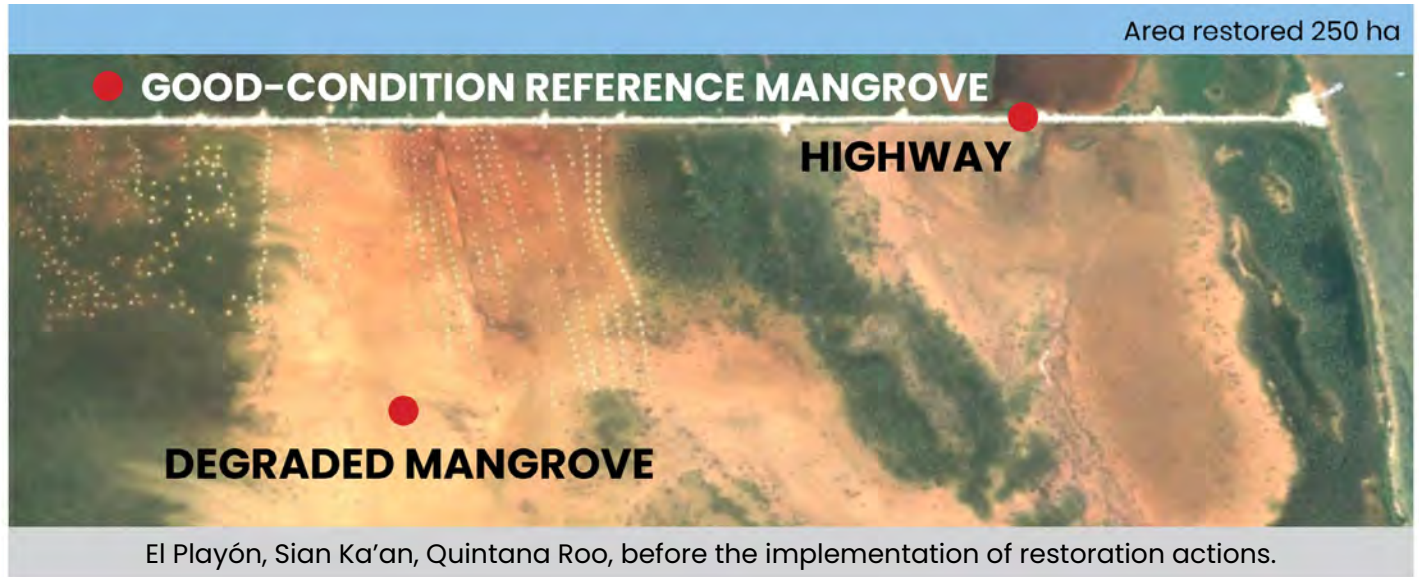
Comparison of the restoration area in 2009 (left panel) and 2019 (right panel).

3.2 Sian Ka'an

Workgroup

Instituto Mexicano de Tecnología del Agua (IMTA), Amigos de Sian Ka'an, The World Bank (MB), Reserva de la Biósfera de Sian Ka'an, CINVESTAV-IPN Unidad Mérida,

Instituto Nacional de Ecología y Cambio Climático (INECC), and inhabitants of the communities of Tres Reyes and X-Hazil.



| Objective | Goals | Criterion | Indicator | Variables |
|--|--|---|--|---|
| Recover ecosystem services that will reduce environmental and social vulnerability to climate change impacts. | Synchronize variations in water level between the channel built and the mangrove being restored. | Hydraulic connectivity. | Hydrology. | Frequency, level, and duration of inundation. |
| | Reduce interstitial salinity by 50% | Physical-chemical characteristics of water. | Salinity reduction. | Salinity of interstitial and surface water. |
| | Promote natural regeneration over a 9-month period. | Natural recruitment and vegetation structure. | Establishment, survival, and growth. | Seedling density, species composition, height, and diameter. |
| | Recover the carbon sequestration capacity of the site in five years. | Reactivation of biogeochemical processes. | Carbon sequestration of the ecosystem. | Carbon in above-ground (biomass) and underground (roots and sediment) compartments. |

Diagnosis:

The construction of a road interrupted the flow of surface water and runoff. This led to differences in hydroperiod between the good-condition reference mangrove and the site to be restored, resulting in the flooding of the mangrove plain and its ensuing hyper-salinization (120–140 g/kg) for long periods of time.

Restoration actions

Natural channels were desilted, water passages were rehabilitated and expanded, and 5,000 meters of new channels were built. These new channels were designed following the microtopography and preferential flows of the site, as identified during the site characterization stage. Topographic elevations devoid of vegetation (from previous restoration initiatives implemented on-site by other research teams) were found and used as dispersal centers (DCs); additional DCs were constructed, and propagules from the good-condition reference site were transplanted.

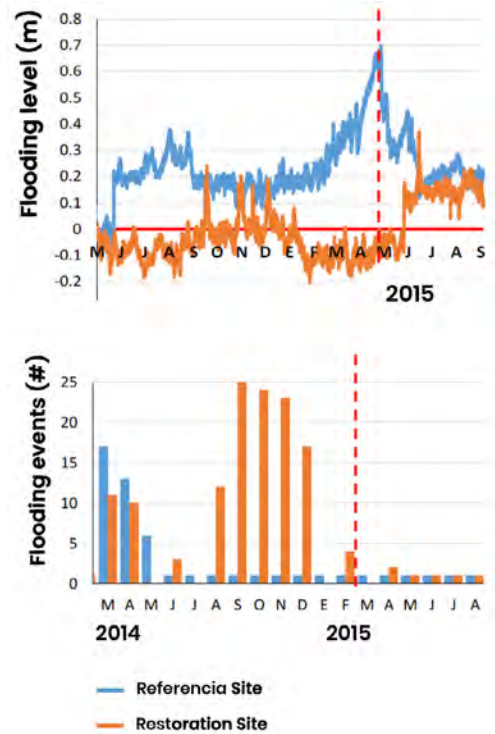
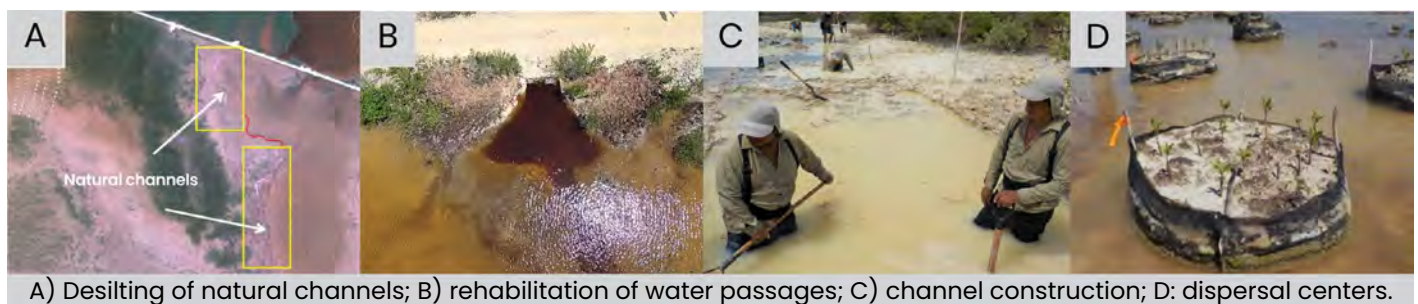


Figure 3.2.1. Hydroperiod components before (2014) and after (2015) hydrological rehabilitation. A) Flood level. B) Number of flood events. The red line indicates the start of hydrological rehabilitation actions [6].



Evaluation

The hydroperiod of the restoration site became synchronized with that of the good-condition reference mangrove within the first month after the start-up of the restoration actions (Figure 3.2.1). Salinity decreased dramatically soon after starting the hydrological rehabilitation works and continued decreasing gradually to an average of 60 g/kg.

Soon after the hydrology was rehabilitated, natural regeneration began on the DCs from the previous project. Natural regeneration began both on the newly built DCs and other sites, where the density of mangrove species increased from 9,153 ind ha⁻¹ in 2016 to 64,178 ind ha⁻¹ in 2019. DCs were spontaneously colonized by *Avicennia germinans*; individuals up to 70 cm tall (Figure 3.2.2 A) were observed in

SUCCESS STORIES

2020, showing a structure similar to that of the good-condition reference low-stature mangrove (average height: 94.5 ± 5.4 cm). The restored mangrove also recovered its carbon sequestration functionality (Figure 3.2.2 B), thus meeting the objective of recovering ecosystem services that reduce environmental vulnerability to climate change.



Dispersal centers in 2020

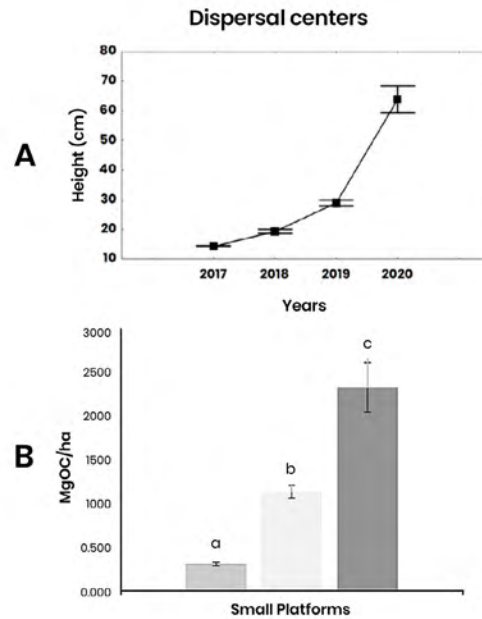
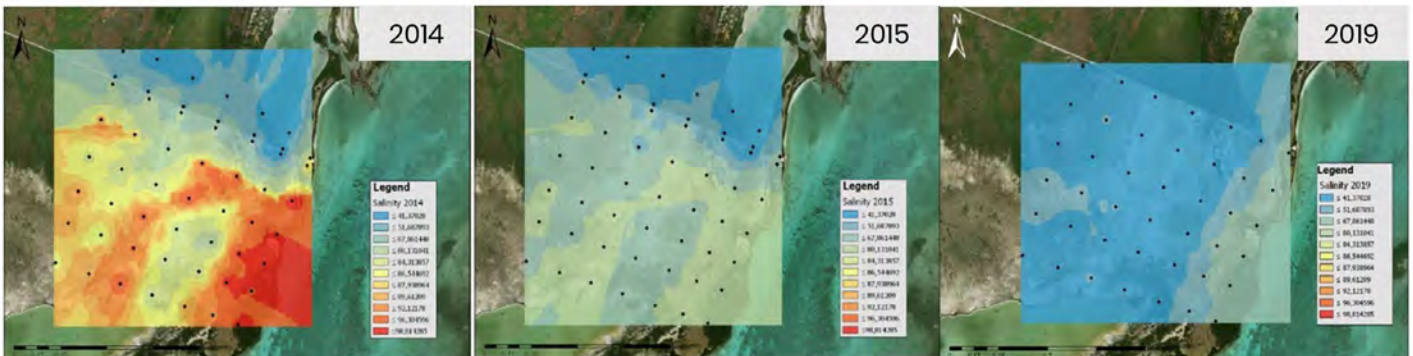


Figure 3.2.2. A) Growth (height), and B) carbon storage of seedlings in dispersal centers. (Graph of Arenas-González ^[44]).



Change in interstitial salinity during the restoration process. The dark blue and red colors represent the lowest (< 41 g/kg) and highest (> 98 g/kg) salinity values, respectively. Figures taken from Arenas-González ^[44].



Comparison of the restoration area in 2009 (left panel) and 2019 (right panel).

3.3 Progreso

Workgroup

CINVESTAV-IPN Unidad Mérida, and representatives from the local delegation of the federal ministry of communi-

cations and transport (Secretaría de Comunicaciones y Transportes-Delegación Yucatán). The group *Chelemeras Unidas por la Restauración del Manglar* was hired by the company IRAVALL CONSULTORES S.A. de C.V.



| Objective | Goals | Criterion | Indicator | Variables |
|--|---|---|--------------------------------------|--|
| Recover the hydrological, structural, and functional characteristics of the disturbed mangrove through actions that improve the environmental sustainability of the site | Synchronize variations in water level between the channels enabled and the mangrove being restored. | Hydraulic connectivity. | Hydrology. | Frequency, level, and duration of inundation. |
| | Reduce interstitial salinity by 30% | Physical-chemical characteristics of water. | Salinity reduction. | Interstitial and surface water salinity. |
| | Promote natural regeneration over a 12-month period. | Natural recruitment and vegetation structure. | Establishment, survival, and growth. | Seedling density, species composition, height, and diameter. |

Diagnosis

The Merida-Progresso highway disrupted the flow of water and surface runoff between both sides of the road, causing the obstruction of natural channels and the ensuing alteration of the hydroperiod. The long flooding periods at the site led to hypersalinity (>100g/kg). These processes drove the loss of the original vegetation.

Restoration actions

The hydrodynamic model constructed during the site characterization stage allowed identifying, based on the topographic level and preferential flows, the areas most suitable for hydrological restoration through intervention (Figure 3.3.1). Natural tidal channels were recovered, and 2,118 m of new channels were built; debris was removed. Besides, topographic leveling of the terrain was carried out at the deepest sites identified from the topographic map, using dispersal centers and materials removed during channel construction.

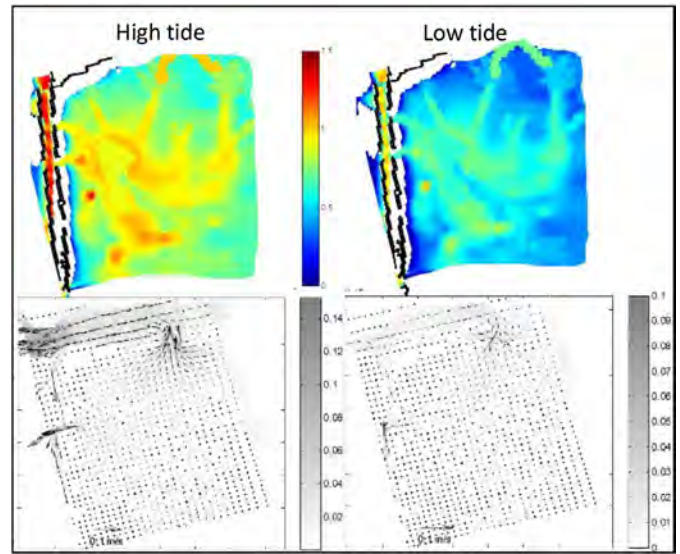


Figure 3.3.1. Hydrodynamic model of the Progreso site constructed from topo-bathymetric data to identify preferential flows. Graph prepared by Ismael Mariño and Cecilia Enríquez.

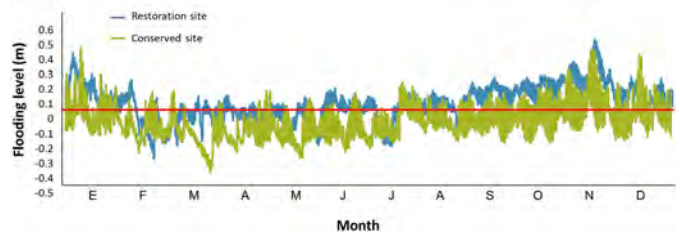


Figure 3.3.2. Flooding level synchronization between the good-condition reference mangrove and the restoration site after restoration, as of 2016. Graph prepared by Oscar Pérez.



A) Rehabilitation of channels to provide hydraulic connectivity and dispersal centers; B) building new channels; C) *Las Chelemeras* women group.

Evaluation

Hydroperiod was restored to a pattern similar to that of the good-condition reference mangrove (Figure 3.3.2), and salinity decreased to 45.7 g/kg on average. Propagules of *Rhizophora mangle* were planted, and *Avicennia germinans* plants established spontaneously on the dispersal centers. These species then established themselves spontaneously in other areas, along with pioneer species such as *Batis maritima* and *Salicornia virginica*. Survival decreased over time due to interspecific competition (Figure 3.3.3 A) and the increased coverage of surviving species (Figure 3.3.3 B).

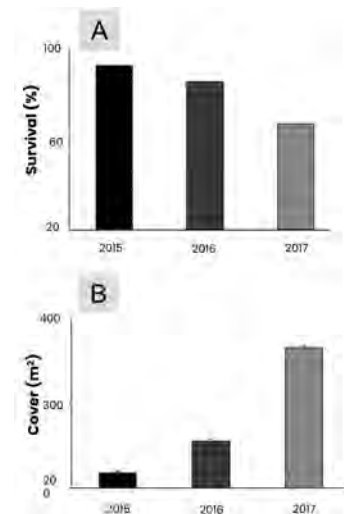
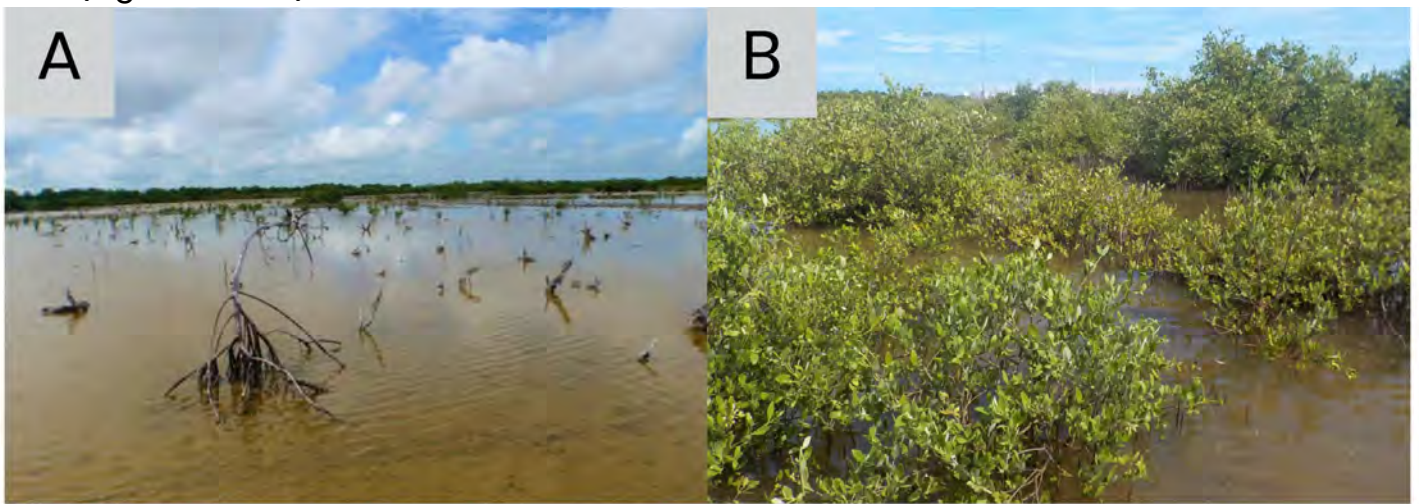
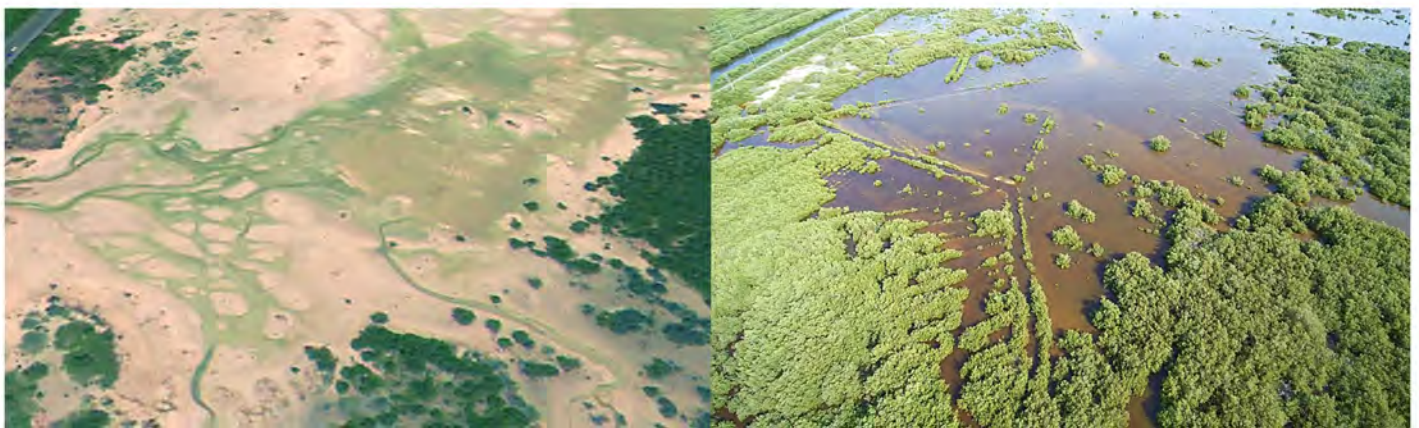


Figure 3.3.3. A) Seedling survival and B) change in vegetation cover of mangrove species over time [7].



A) Before (2009) and B) After (2019) restoration.



Comparison of the restored area in 2009 (left panel) and 2019 (right panel).

4. LESSONS LEARNED

- Set up an **inclusive workgroup** from the beginning of the project, formalizing the commitment of its members through group agreements and institutional arrangements, and defining their participation level and the benefits they will receive from the project (2.1.1).
- **Involve the local community** from the beginning of the project, during the implementation stage, and in evaluation and completion activities (2.4).
- **Include in the budget the costs of monitoring, environmental education workshops, and capacity building.**
- Clearly define **what, how, when, where, and costs** for the restoration to achieve the objectives and goals set (2.1.2).
- **Information specific to the site to be restored is indispensable;** information or knowledge imported from other restoration areas is rarely useful (2.1.3).
- Carry out a comprehensive **forensic ecology analysis** (site characterization) to identify the causes of mangrove forest degradation and the initial conditions of the degraded mangrove (2.1.3).
- **Identify a set of site-specific restoration actions** based on the results from the forensic ecology analysis (2.1.3)
- Establish **permanent sampling points** for the entire restoration process and its monitoring using success indicators (2.3.1). Additional sampling points might be necessary later on as the landscape is being reconfigured.
- Evaluate restoration using hydrological, biological (plants and organisms), and sediment variables from which **short-, medium-, and long-term indicators are calculated.** Evaluation allows adjusting restoration actions through an adaptive management approach to increase the likelihood of achieving the objectives and goals (2.3.1).
- **Identify and promote alternative productive activities** derived from the ecosystem services recovered by the restoration project (3.1).
- Evaluate the ecological restoration project comprising not only ecological aspects but also the **social and economic components** (2.3.1).
- Include in the project an **outreach strategy** for the local, regional, and national levels (2.4).
- **Communicate project results** through non-formal mechanisms (e.g., popular science articles, newspaper notes), but also through formal ones (e.g., scientific articles and technical documents) to contribute to advance the theoretical framework of restoration ecology (2.4).

REFERENCES

1. SER (Society for Ecological Restoration International Science & Policy Workgroup). 2004. www.ser.org
2. Estrategias de restauración de manglares de México: el caso Yucatán. En Experiencias mexicanas en la restauración de los ecosistemas. UNAM, CRIM, UAEM. CONABIO. 2016. ISBN: 9786070281570.
3. Restauración ecológica de manglares en México. En Gobernanza y Manejo de las Costas y Mares ante la Incertidumbre Una Guía para Tomadores de Decisiones. 2020. ISBN: 978-6078-444.
4. Conceptual framework for mangrove restoration in the Yucatán Peninsula. *Ecological Restoration*, 28(3): 333-342. 2010.
5. Rehabilitación de manglares en el estado de Yucatán sometidos a diferentes condiciones hidrológicas y nivel de impacto: el caso de Celestún y Progreso. Centro de Investigación y de Estudios Avanzados. Unidad Mérida. Informe Final SNIB-CONABIO. Proyecto GH009. 2012.
6. Rehabilitación hidrológica: producto "C". Proyecto: Implementación De Medidas De Adaptación para reducir la vulnerabilidad ante los impactos del cambio climático de la comunidad de Punta Allen (Reserva De La Biosfera De Sian Ka'an) A través de la rehabilitación de un ecosistema de manglar en el humedal "El Playón". CINVESTAV, Amigos de Sian Ka'an, ANP de Sian Ka'an, INECC, IMTA -CNA. GEF. 2015.
7. Adaptación de ecosistemas costeros al cambio climático en áreas naturales protegidas de México, con énfasis en la captura y reducción de emisiones de carbono en humedales. Informe Técnico Final. ENDESU-IN-ECC-SEMARNAT-CINVESTAV. 2017.
8. *Global environmental change*, 26: 152-158. 2014.
9. Mangrove restoration potential-A global map highlighting a critical opportunity. IUCN. University of Cambridge. NC. 2018.
10. *Annual Review of Environment and Resources*, 44: 89-115. 2019.
11. Contributions of workgroups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC. 2007.
12. *Science*, 317 (5834): 41-42. 2007.
13. Nature-based Solutions to address global societal challenges. IUCN. 2016.
14. *Ecological Restoration*, 23: 181-186. 2005.
15. *Wetlands Ecology and Management*, 16 (5), 345-358. 2008.
16. Una aproximación a la integración de escalas ecológicas para la restauración de ecosistemas de manglar. Tesis Doctoral. Univeristat de Barcelona. 2017.
17. *Restoration Ecology*, 25: 668-673. 2017.
18. Problems of scaling in restoration ecology: a practical application. En: *Restoration Ecology: a Synthetic Approach to Ecological Research*. Cambridge University Press.1987. ISBN: 9780521337281.
19. *Estuaries and coasts*, 32(1): 1-17. 2009.
20. *Ecological Indicators*, 60: 442-452. 2016.
21. *Marine and Freshwater Research*, 49(4): 309-323. 1998.
22. *Ecological Research*, 19(1): 75-81. 2004.
23. *Marine Pollution Bulletin*, 37(8), 383-392. 1999.
24. *Ecological engineering*, 24(4):403-418. 2005.
25. Rehabilitación Ecológica del Manglar. Manual de campo para Rehabilitadores. Mangrove Action Project. 2014.
26. *Marine Pollution Bulletin*. 37: 373-382. 1998.
27. Mangrove restoration Costs and benefits of successful ecological restoration. In *Proceedings of the Mangrove Valuation Workshop*, Universiti Sains. 2001.
28. *Ecological Applications*, 26(4): 1055-1074. 2016.
29. *Journal of Coastal Research*, 40: 79-93. 2005.
30. Ecological restoration: a global challenge. 2010. ISBN: 9780521877114.
31. *Conservation Biology*, 29(2): 493-502. 2015.
32. Métodos para la caracterización de los manglares mexicanos: un enfoque espacial multiescala. CONABIO. 2018. ISBN: 9786078570034.
33. *Annual Review of Marine Science*, 2: 395-417. 2010.
34. *Journal of the Fisheries Research Board of Canada Bulletin*. 122: 311. 1972.
35. A manual of chemical and biological methods for seawater analysis. Pergamon press, 1984. ISBN: 9780080302874.
36. Métodos para la descripción y estudio de áreas de manglar. Ingeniería marítima, Ciencias del mar. Escuela superior Politécnica del Litoral. 1990.
37. *Ecological Engineering*, 37(2): 113 - 122. 2011.
38. *Ecotropicos*, 19(2): 72-93. 2006.
39. FAO. Mangrove forest management guidelines. 1994.
40. *PLoS Biology*, 10 (1) | e1001247. 2012.
41. *Wetlands Ecology and Management*,17: 365-383. 2009.
42. *Ecological Engineering*, 130, 263-270. 2019.
43. *Revista mexicana de biodiversidad*, 87(2), 489-496. 2016.
44. The potential of blue carbon in Management in Mexico: a case study from the biosphere Reserve of Sian Ka'an. Master Thesis. The University of Manchester. Manchester, United Kingdom. 2019.



"It always seems impossible until it's done".

-Nelson Mandela

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