

# Conceptual Framework for Mangrove Restoration in the Yucatán Peninsula

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## ABSTRACT

Mangrove loss in Mexico led to the development of different recovery programs focused on building and maintaining greenhouses, reforestation, and the construction of drainage systems along coastal roads to reestablish surface water flows. However, these recovery strategies have not been as successful as expected because they were not based on an evaluation of environmental characteristics required for mangrove development in the context of new hydrological and sedimentary conditions. The studies performed over the last ten years by the mangrove group at Centro de Investigación y de Estudios Avanzados (CINVESTAV), in collaboration with other institutions, resulted in a conceptual framework that we present here as a methodological approach for the ecological restoration of mangroves in the Yucatán Peninsula. The conceptual framework is based on the relationships among the geomorphology, hydrology, and structural and functional characteristics of mangroves that are associated with the environmental services offered by these ecosystems. The methodological approach is fundamentally concerned with the particular characteristics of the karstic environmental setting of the Yucatán Peninsula as well as social and economic aspects of restoration. This approach to mangrove restoration includes stages for planning, implementing, and monitoring mangrove restoration programs in karstic environments.

## RESUMEN

La pérdida de manglares en México ha llevado al desarrollo de diferentes programas para abordar su recuperación. En la Península de Yucatán estos programas se han centrado principalmente en la construcción y mantenimiento de invernaderos, la reforestación y la construcción de sistemas de alcantarillas en las carreteras costeras para restablecer los flujos de las aguas superficiales. Sin embargo, estas estrategias de recuperación no tuvieron el éxito que se esperaba, principalmente porque no se basaron en la caracterización ambiental como un criterio para identificar las condiciones hidrológicas y de sedimentos necesarias para el desarrollo de manglares. Los estudios realizados durante los últimos diez años por el grupo manglares en el Centro de Investigación y de Estudios Avanzados (CINVESTAV), en colaboración con otras instituciones, han dado lugar a un marco conceptual que se presenta aquí como un enfoque metodológico para la restauración ecológica de los manglares en la Península de Yucatán. El marco conceptual se basa en las relaciones que hay entre la geomorfología, la hidrología y características estructurales y funcionales de los manglares, y que están asociados con los servicios ambientales que ofrecen estos ecosistemas. El enfoque metodológico es fundamentalmente relacionado a las características particulares del entorno kárstico de la Península de Yucatán, así como aspectos sociales y económicos de la restauración. Este enfoque de la restauración de manglares incluye las etapas de la planificación, implementación y seguimiento de los programas de restauración de manglares en ambientes kársticos.

**Keywords:** hydrology, mangrove restoration, restoration indicators, Yucatán

**Palabras clave:** hidrología, indicadores para la restauración, restauración de manglares, Yucatán

Mangrove ecosystems are wetlands located in tropical and subtropical intertidal zones. The vegetation of these wetlands consists of

halophytes, which are arboreal and shrubby in form (Lugo and Snedaker 1974). Their role in chemical, physical, and biological connectivity with other coastal ecosystems such as seagrasses and coral reefs is well known (Mumby et al. 2004). In the tropical coastal zone, salinity and variable flooding conditions, strong winds,

high temperatures, and unstable and anaerobic sediments exist. As a result, mangrove species possess particular morphological and physiological characteristics adapted for growing in these locations, enabling them, for example, to withstand and grow in totally or partially flooded anoxic environments subject to pounding from tides and

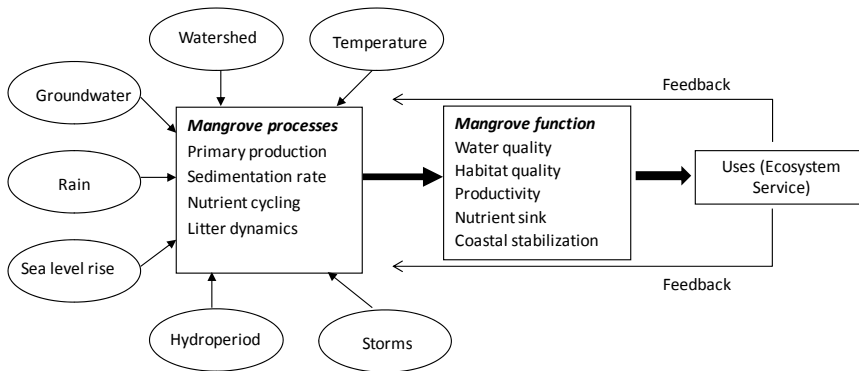


Figure 1. Conceptual framework of ecological forcing, functions, and environmental services on mangrove ecosystems (modified from Twilley 1995). Abiotic forcing factors influence ecological processes, which in turn affect ecological function and ecosystem services. Human uses can provide negative feedback, producing changes in the mangrove function.

hurricanes (Mitsch and Gosselink 1993).

The ecological processes that take place in mangroves have a close relationship with geomorphological, hydrological, and climatological factors (Figure 1). To a large extent, these factors determine the structure and function of mangroves, including biodiversity, species dominance, nutrient dynamics, and primary productivity. These characteristics are associated with their capacity to provide goods and services, such as protection and stabilization of the coastline, improvement of water quality, and provision of a breeding and feeding area for fauna of ecological or commercial importance (Twilley 1995, Ewel et al. 1998). These environmental services are associated with many human uses; however, lack of knowledge about mangrove ecosystem function has in some cases resulted in extensive damage that is difficult to quantify and with many negative environmental repercussions (Field 1996). The frequency and magnitude of natural and anthropogenic disturbances of mangroves is reflected in the loss of their self-regulation, degradation, tree death, and the resultant loss of the ecosystem services they provide.

## Mangrove Loss and Restoration

The loss of mangrove cover is a worldwide concern. Mangroves decreased an estimated 35% between 1980 and

2000, equal to a loss of approximately 2.07% per year (Valiela et al. 2001). The origins of mangrove decline are greatly varied, but main causes include construction of tourist and port infrastructures, conversion to agriculture and extensive cattle raising, shrimp aquaculture, coastal road construction, human settlements, and petroleum industry development.

The national total area of mangroves calculated for Mexico is still a topic of debate. However, the most up-to-date figures have been reported at 770,057 ha, with 66% located on the Atlantic coast and 34% on the Pacific coast (CONABIO 2009). The annual rate of loss in mangrove area between 1976 and 2000 was between 1% and 2.8%, with an estimate of 1.84% for Yucatán (INE 2005). This loss has led to a number of mangrove recovery efforts by federal and state institutions (CONAFOR 2010a). Between 1995 and 1998, seawater control structures were constructed to reduce marine water inputs to mangrove zones and to minimize salinization impacts of road construction. In 2000, the North American Wetlands Conservation Council gave the Yucatán state government US\$800,000 for mangrove restoration efforts (SEMARNAT 2000).

According to Teutli-Hernandez (2003), restoration goals were not achieved by these mangrove recovery efforts. The vast majority of restoration efforts have lacked a technical basis, an ecosystem approach, and long-term

programming and have primarily used reforestation as a solution, with little success. Among the main causes for the failures are the lack of baseline information concerning the hydrology, sediments, and topography of the sites to be recovered. As a result, there are no criteria available for deciding which sites are viable for restoration or rehabilitation. Nongovernmental organization initiatives have concentrated their efforts on reforestation and the promotion of mangrove nurseries (Tovilla-Hernández and Orihuela 2002). In addition, most mangrove recovery projects in Mexico are based on legal policies, such as environmental compensation (SEMARNAT 2003), and do not focus on ecosystem recovery (Figure 1).

In contrast, this study presents a methodological approach that maximizes the resources and results of mangrove recovery in the Yucatán Peninsula. This approach is based in the experiences described by Rivera-Monroy and others (2001), Lewis (2005, 2009), and Twilley and Rivera-Monroy (2005), as well as the projects developed by the authors, and has the central strategy of recovering ecosystem structure and function and ecosystems services, based on environmental characterization and diagnosis, restoration action and monitoring, and local stakeholder participation.

## Mangroves of the Yucatán Peninsula

The Yucatán Peninsula is located in the southeast region of Mexico (Figure 2), where the climate is typically hot and humid and characterized by three seasons: dry (March to May), rainy (June to October), and cold fronts called “nortes” (November to February). Average rainfall varies between 400 and 2,500 mm per year, with an average evaporation rate of 2,000 mm per year. The tidal regime characteristic of the Yucatán coast is that of a mixed semidiurnal tide of 0.6 m (Herrera-Silveira 1994).

Extensive areas (423,751 ha) of mangroves are characteristic of the Yucatán coasts, particularly in the states of Quintana Roo and Campeche, but they also suffer the greatest rates of annual loss (> 3%). This region of Mexico has geohydrological karstic characteristics of tropical zones, with semiarid coasts, high hurricane frequency, oligotrophic soils, a tidal regime between 0.2 m and 0.6 m, and freshwater inputs mostly from subterranean discharges via springs that flow into the mangrove wetland, coastal lagoons, and marine areas (Herrera-Silveira and Comín 2000). This freshwater source is characterized by its large inputs of inorganic nitrogen (> 60  $\mu\text{M}$ ) and silicates (> 300  $\mu\text{M}$ ) and low particulate matter content (< 1 mg/L) (Herrera-Silveira 1994), which have an influence on the formation of environmental gradients (mainly salinity) and nutrient dynamics. These environmental settings are responsible for the spatial and temporal patterns in the structure and function of mangrove ecosystems, from species development to landscape level (Herrera-Silveira 1993, Zaldívar Jiménez et al. 2004), and ecologically distinguish the Yucatán Peninsula from the rest of the country. Therefore it is important to understand how local and regional environmental characteristics determine the different patterns in the structure and function of mangrove forests, as this is vital for developing management programs that include ecological restoration, facilitating the recovery of ecosystems that have been degraded, damaged, or destroyed (SER 2004).

It has been suggested that since the Yucatán Peninsula is a karstic platform of low elevation (slope < 1%), has rough topography, and is exposed to hurricanes, the area is highly vulnerable to the effects of climate change (Yáñez-Arancibia et al. 1998, Pannier 1992, Ortiz Pérez and Méndez Linares 2000). The geomorphology of the Yucatán Peninsula favors the formation of water bodies that are either seasonally flooded (swamps such as

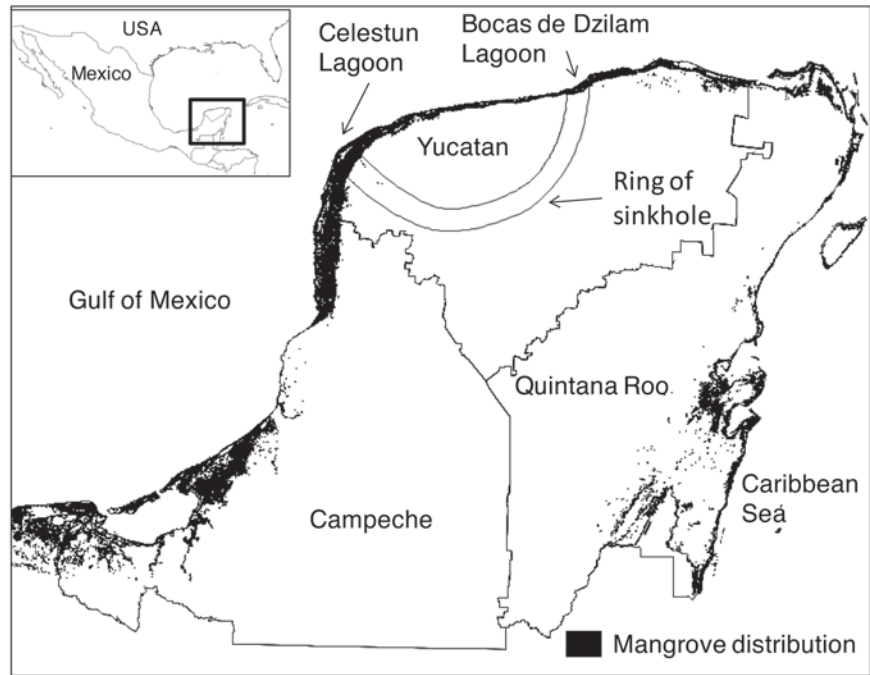


Figure 2. Mangrove locations in the Yucatán Peninsula, Mexico.

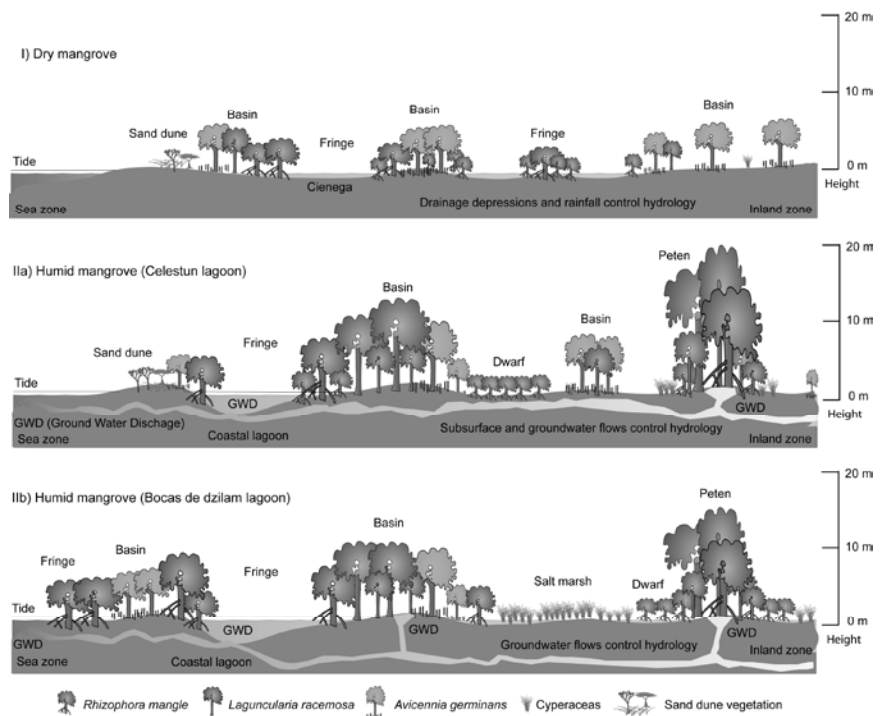


Figure 3. Mangrove forest types in dry (seasonally flooded) and humid (permanently flooded) Yucatán environments, each with different mangrove species and spatial distributions of the four structural types: fringe, basin, dwarf, and petén.

those at Progreso, Sisal, and Palmar) or permanently flooded (coastal lagoons such as Celestún, Chelem, and Dzilam) (Figure 3). In both cases, these bodies of water are bordered by mangrove forests dominated by one or a mixture of two or more species:

red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*), white mangrove (*Laguncularia racemosa*), and button mangrove (*Conocarpus erectus*).

Structurally, the mangroves in the Yucatán Peninsula can be fringe, basin,

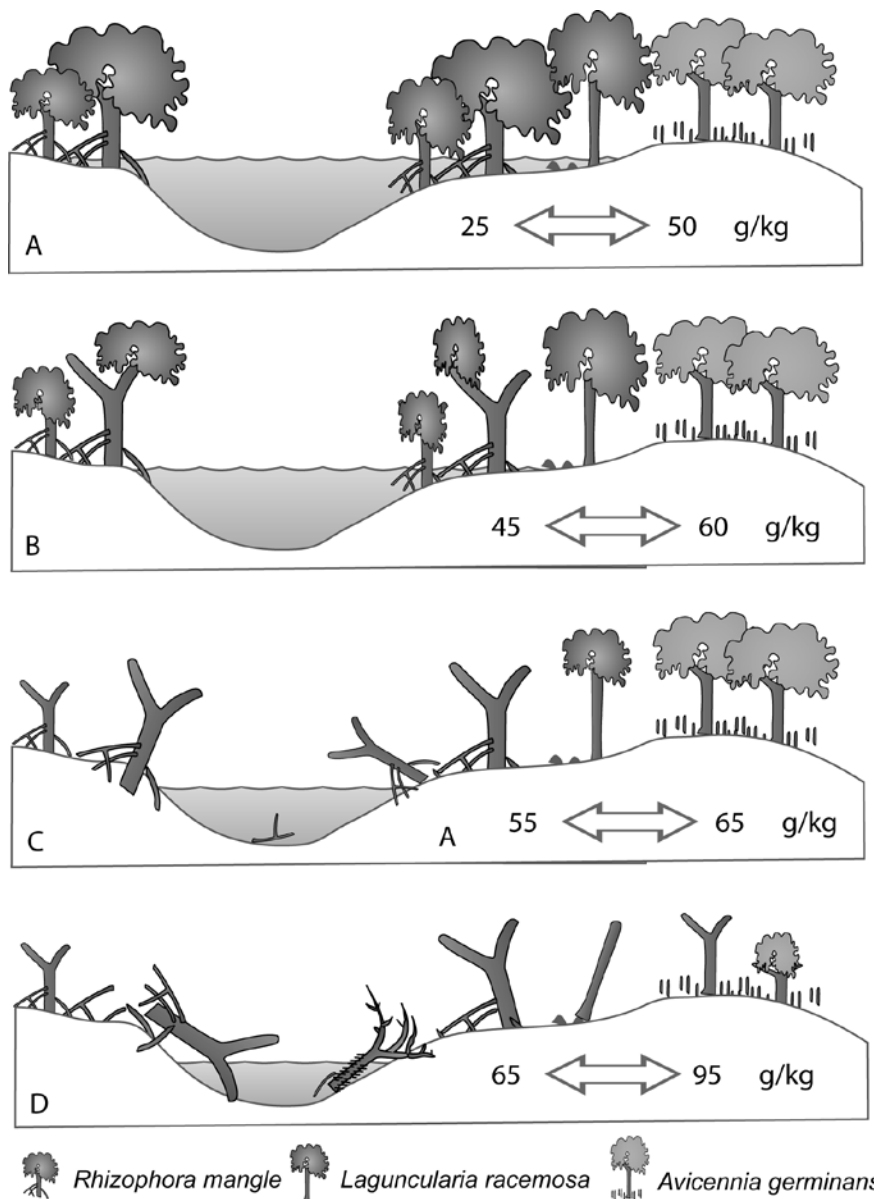


Figure 4. Soil salinization is the main cause of degradation in Yucatán mangroves, and each mangrove species has a different response as shown in this sequence of increasing soil salinity: a) mangroves in a healthy state; b) increasing soil salinity in fringe mangroves creates negative impacts, particularly on the red mangrove (*Rhizophora mangle*); c) soil salinity increase and reduced flooding kill red and other mangrove species; and d) in the highest soil salinity ranges only the black mangroves (*Avicennia germinans*) can survive in low densities as a dwarf forest.

dwarf, or petén (a specific name given in Yucatán given to small areas with high and dense tree development surrounding freshwater springs), dominated by one species (red, white, or black mangroves) or a mixture of the three (Herrera-Silveira et al. 2000, Zaldívar-Jiménez et al. 2004). Fringe mangroves are primarily dominated by red or white mangrove, depending on the salinity and level of flooding, and are located on the edge of lagoons (for example, Celestún and Dzilam)

or swamps (Sisal and Progreso), or directly in front of the sea (Dzilam) in direct contact with the water body. These mangroves are generally vulnerable to changes in the level of tidal inundation.

Basin mangroves are located behind fringe mangroves and are generally hydrologically isolated, flooding only during extraordinary tides, storm, or hurricane events, or during the months of maximum rainfall. As a result, the interstitial salinity in basin

mangroves is high (> 50 g/kg), and they are generally dominated by black mangrove. However, where salinity is low (< 30 g/kg) the dominant species can be the white mangrove.

Dwarf mangroves are located behind basin mangroves or directly in front of a body of water. Their structure is associated with stress caused by a deficiency in resources (nutrients such as phosphorus) or hydrological stress (changes in hydroperiod or interstitial salinity) (McKee 1995, Twilley and Rivera-Monroy 2005). The vegetation of petén mangroves is associated with a direct freshwater input (spring), leading to well-developed structures similar to mangroves in humid areas. These mangroves can be identified as large domes of vegetation within grassy areas (Durán García 1995).

Another important factor in management, restoration, and rehabilitation programs is the effect of tropical storms and hurricanes. Mangroves in the Yucatán Peninsula have been heavily impacted by the winds and waves of hurricanes, with five hurricanes passing over the area between 1988 and 2007. In Dzilam in 2002, the loss in cover due to hurricane "Isidoro" was estimated to be between 10% and 70% (Herrera-Silveira et al. 2004). The impacts that hurricanes have on a mangrove community are primarily caused by winds, water currents, the erosion and deposition of sediments, and changes in hydrological and sediment conditions, all of which hinder the community's recovery and which can vary widely at different sites (Herrera-Silveira et al. 2004).

In Mexico, there are few studies concerning the rehabilitation and restoration of mangrove forests. A reforestation program is described in the Global Restoration Network (Benítez Pardo 2008) for 11 ha of mangroves on islets formed by dredged material along the semiarid coast of Sinaloa. A similar program focuses on the reforestation of dredged material deposited along the coast of Chiapas (Tovilla Hernández et al. 2004).

Federal programs are generally focused on the construction of mangrove greenhouses and the number of plants produced in greenhouses or planted in the field (CONAFOR 2010a). The success of these programs is evaluated by the number of mangrove seedlings generated in the greenhouse, without consideration for the actual area reforested (CONAFOR 2010b). In Yucatán, mangrove restoration programs have, in most cases, focused on reforestation and not on the rehabilitation of the hydrological conditions needed for mangroves. Stevenson and others (1999) refer to this approach of simply planting mangroves as “gardening.” Furthermore, these programs have been carried out on a trial-and-error basis, and there has not been a learning process.

In the Yucatán Peninsula, changes (both human-caused and natural) in the frequency, level, and time of flooding of mangroves have been the main cause for their decline. Mangroves that suffer long periods (> 3 months) of drought or flooding (primarily salty water) experience low rates of establishment and growth of seedlings (which drown or desiccate), increases in interstitial salinity (>80 psu, Figure 4), reduced redox potential of the sediments (McKee et al. 1988), and increases of sulfide concentrations (indicated by the odor during sediment extraction, creating sediment conditions physiologically intolerable to mangrove species). The main action in hydrological rehabilitation projects is the construction and desilting of canals to facilitate the recovery of the hydroperiod and reduce the salinity of the sediments, thereby stimulating the reestablishment of major ecosystem functions and natural regeneration. Reforestation remains a last option. However, these approaches have been successful on less than 1% of the area in need of recovery (Teutli-Hernández 2003). At present, projects that favor natural regeneration are being developed in Celestún and Progreso (Herrera-Silveira et al. 2009).

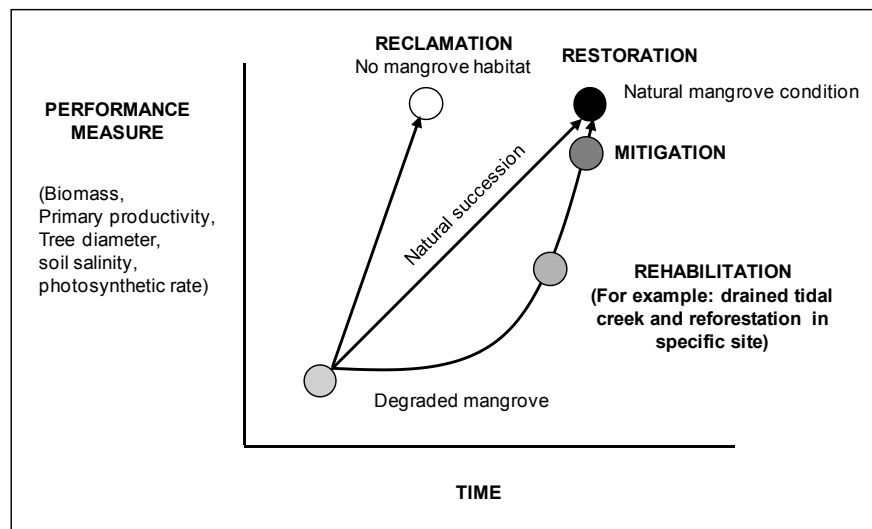


Figure 5. Conceptual framework for mangrove restoration processes (adapted from Kentula et al. 1992, Hobbs and Mooney 1993).

### A Conceptual Framework for Restoring Yucatán Mangroves

Different terms have been used to describe efforts made toward recovering mangrove ecosystems, including rehabilitation (reforestation and hydrological rehabilitation), reclamation (forestation), mitigation, and restoration (Figure 5). These efforts fulfill different objectives, which can include the recovery of structure beginning with plant cover and landscape improvement and rehabilitation of ecological functions, which favor the recovery of ecosystems services (Field 1996, Cahoon and Lynch 1997, Ellison 2000, Rivera-Monroy et al. 2004). The understanding of these concepts makes it possible to evaluate restoration projects (Field 1998, Twilley et al. 1999, Rivera-Monroy et al. 2001).

In this study, rehabilitation is defined as the combination of actions for the partial recovery of the ecosystem’s structural or functional characteristics that have been reduced or lost, with the view that these actions will support the recovery of economic, social, or ecological value lost in currently degraded and perturbed ecosystems (Untawale 1996, Field 1996). With respect to mangroves, reforestation refers to the introduction of forest species in an area where they

previously existed, while a forestation refers to planting trees in areas where they were not originally established (Valdez Hernández 2002). Reforestation and hydrological reestablishment via physical infrastructure are considered to be rehabilitation measures.

In comparison, afforestation would be a form of reclamation, which implies a change in the structure and function of a degraded ecosystem such that ecological restoration is not viable. The main objectives of reclamation include the stabilization of land, the assurance of public safety, aesthetic improvement, and in general the return of the land to what would be considered a useful condition within the regional context (SER 2004). Mitigation refers to all actions that tend to minimize the impacts of natural (hurricanes, for example) or anthropogenic events on ecosystems (Bradshaw 1984). The concept of “creating an ecosystem” has recently been used to refer to mitigation projects that are carried out on completely bare land (SER 2004).

The restoration concept is more restricted, referring to the actions of returning an ecosystem as closely as possible to its original state. In this paper, we adopt the definition of ecological restoration as the “process of assisting the recovery of an ecosystem

**Table 1. Ecological indicators and implications of physical and chemical variables in an environmental monitoring program for mangrove forests in the Yucatán Peninsula. These variables can be considered as performance measurements (success indicators) in an ecological restoration.**

Ecological Indicator	Performance Measures	Ecological Implications
Mangrove structure and regeneration	Species dominance Forest structure index Seedling, sapling, and tree density	Forcing functions determine the presence and absence of mangrove species. Dominance can indicate that a species is specialized and therefore difficult to restore. Age class distribution suggests the potential regeneration pattern of a site.
Hydrological patterns	<i>Flooding</i> (hydroperiod): level, frequency, and period <i>Water</i> : source, temperature, and moving processes Groundwater discharge Soil salinity Precipitation/evaporation rate	Seedlings of different species have varying susceptibilities to flooding (e.g., <i>Rhizophora mangle</i> tolerates < 10 cm flooding). Hydroperiod controls the soil conditions. The source of water is important. Each mangrove species has different physiological capacities for coping with a hypersaline (> 50 g/kg) environment.
Soil	Organic matter (OM) Bulk density and nutrients (CNP) Sulfides Microtopography	Soil nutrients indicate fertility; carbon-nitrogen-phosphorus ratios determine vegetation growth. Bulk density indicates the dominant soil materials (low bulk density = high OM). Sulfide concentration varies with hydrology, and greater levels cause stress and death of mangroves. Soil elevation and topography determine the hydrological dynamics of mangroves.

that has been degraded, damaged or destroyed” (SER 2004). Ecological restoration requires the integration of scientific, economic, and social aspects (Comín 2010). In this paper, we put emphasis on the scientific component, suggesting the following five key elements for mangrove restoration projects in the Yucatán Peninsula.

## 1. Identification of the Site and Objectives

Ecological restoration projects should clearly establish objectives: 1) where an ecological restoration effort should focus; 2) what is to be recovered (functions, processes, structure, environmental settings); 3) how best to carry out recovery actions, which should be based on robust science that supports the development of the theory of mangroves restoration; and 4) how the project will be measured, and over what spatial and temporal time scales.

In the case of Yucatán mangroves, and according with SER’s (2004) definition of ecological restoration, we propose that the primary objective should be the recovery of ecosystem

function, so that the ecosystem may self-regulate, recover its resiliency, and provide more ecosystem services. The participation of scientists, organized social groups, and funders is critical in order to discuss and define the site, subject to ecological restoration and the aims of each participant.

## 2. Characterization of the Site and Impact Analysis (“Forensic Ecology”)

A key element in restoration projects is to determine site characteristics, at both local and landscape levels, and to identify the causes for the decline and death of mangroves. This is an investigative job similar to that of forensic medicine, and we have called this process “forensic ecology.” Baseline information before the deterioration is often missing, and it is important to look for clues regarding the earlier environmental setting. This can sometimes be determined by using a reference site for comparison.

Analyses of aerial photographs and satellite images can help identify the speed at which change occurred. Once

a site and the causes of problems have been identified, the geomorphological, hydrological, and biological variables need to be described (Table 1). Conditions should be compared with a similarly located reference site. In the Yucatán, we have used sites in good condition, located close to the restoration site, and with similar geomorphological and hydrological conditions. Other approaches include comparing the results of restoration with standard indicators. The selection of reference site will depend, among other things, on the available resources, time, and the objectives of the investigation (Kolka et al. 2000, Henry et al. 2002, Stein and Ambrose 1998). If a reference site or condition is not available, objectives for restoration can be established based on social demands combined with planned provision for restoring ecosystem services (Comín 2010).

Once the reference site has been established, the variable or variables to be measured over time will be selected and the information analyzed in the context of performance curves (Figure 6). These curves provide a way of following the development of an ecological

function or structural criteria measured by performance over time in relation to the values observed in a reference ecosystem (Twilley et al. 1999; Twilley and Rivera-Monroy 2005).

### 3. Actions and Measures

The objective of this stage is to implement restoration efforts most appropriate for the specific site chosen. Stakeholders participate in the implementation, supervision, and monitoring of the actions chosen in stage 2. The costs and sources of funding should be defined in order to make the project economically viable. Rehabilitation measures will be specific for each site, but in general the main actions recommended for ecological restoration of Yucatán mangroves are the following:

*Desilting springs*—In sites where springs are common, or in petén mangroves, hurricanes and the accumulation of organic material through time can cause a gradual or sudden decrease in the freshwater inputs from the springs. To reestablish previous hydrological conditions, it is recommended that the springs be desilted (Figure 7). Actions consist of removing all the accumulated mud and dead tree trunks in order to increase the flow of fresh water. These actions can be done by hand or using water pumps.

*Creating new springs*—In sites where hydrological changes have increased water temperature and interstitial salinity, and where there are no nearby freshwater inputs, excavating artificial springs to dilute salinity and to reduce temperatures may be an option. The spatial influence of this solution ranges only from a few to tens of meters, though this could be increased by digging channels that direct fresh water toward the sites (Figure 7). These actions could be done by hand or using an excavator.

*Opening or desilting canals*—Where roads obstruct surface water flow, or where the exchange of water with the sea, springs, or coastal lagoons has decreased, the opening of new

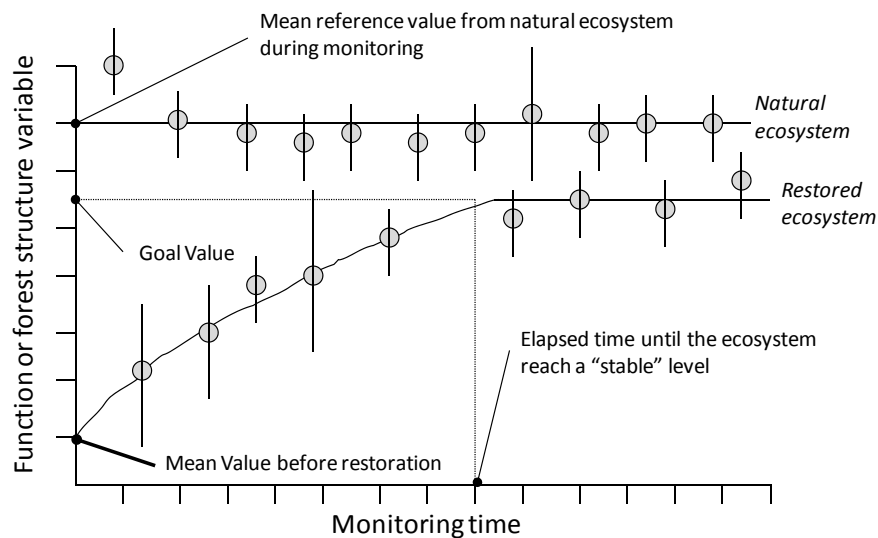


Figure 6. Conceptual diagram of performance curves, including changes in reference and restored ecosystems through time. The performance curve can be used to evaluate the effectiveness of ecosystem restoration and to improve recovery trajectory forecasts (adapted from Twilley et al. 1999, Twilley and Rivera-Monroy 2005, Rivera-Monroy et al. 2006).

channels or the desilting of natural channels is recommended to reestablish the exchange of surface water and groundwater (Figure 7). The location and dimensions of the canals will depend on the results of stage 2.

*Construction of elevated sediment beds*—In areas where basins form and salty or brackish water accumulates, establishing sediment “beds” is recommended in order to create topographic heterogeneity and maintain the maximum water level below the average height of seedlings and saplings. This procedure is recommended in sites where inundation is greater than 0.4 m, interstitial salinity varies between 50 and 80 g/kg, and sediments are dominated by clay material with low organic matter content.

### 4. Monitoring Indicators of Success

Monitoring programs should select specific variables that function as indicators of success for specific restoration programs. These variables should cover a range of ecosystem characteristics from the physiological to landscape level (Table 1). Monitoring can indicate problems and progress, and monitoring adaptively can open up the possibility of applying new actions.

### 5. Publicizing Restoration

Independent of the level of success achieved, the experiences of ecological restoration are important to share. The successes and failures of restoration and reforestation programs in the Yucatán Peninsula have rarely been documented (Teutli-Hernández 2003), and when documented, they tend to be in technical language inaccessible to many people living nearby (Lindig-Cisneros and Zedler 2005). Involving stakeholders in ecological restoration programs from the start of the project, and providing ways for them to participate in both planning and technical implementation, is critical.

Ecological restoration of mangroves in the Yucatán Peninsula should not be centered on greenhouse technology or reforestation, or based on trial and error. Previous projects have been shown to be deficient in both technical and experimental design, resulting in seedling mortality in up to 100% of the reforested area (Teutli-Hernández 2003). Major efforts need to focus on the reestablishment of disturbed forcing functions, or the physical forces (Figure 1; for example, water flows and sedimentation) that drive the structure and function of mangrove forest



Figure 7. Before and after restoration efforts in degraded Yucatán mangroves: desilting springs (top), creating springs (middle), and opening or desilting canals (bottom). Photos courtesy of Eduar Ciaú

water flows from the continent and the sea to the mangrove zone. Direct planting of mangrove trees may be required for specific sites or to accelerate mangrove recovery within the spatial and temporal framework of the previous perspective.

## Conclusion

Reforestation, desilting of springs, and construction and removal of artificial ridges and water passages are all practices that have been used to restore degraded Yucatán mangroves but which have not achieved the expected results. In some cases, these practices have increased degradation.

Our protocol for ecological restoration of Yucatán mangroves is not a recipe for the recovery of all mangroves, but rather presents a technical and systematic procedure. The trajectory of restoration or rehabilitation will depend on the type and magnitude of the disturbance and impact, as well as the target environmental conditions. The procedure presented here begins with site identification and the determination of causes of mangrove deterioration and death, as well as the characterization of existing environmental conditions and objectives. Subsequently, actions to accomplish ecological restoration objectives need to be identified. Finally, a monitoring program should be implemented to evaluate the effectiveness of adaptive management strategies. This approach should at all times consider economic viability and the participation of federal, state, and local stakeholders.

The speed at which mangroves in the Yucatán Peninsula have declined and the growing need for the recovery of their environmental services highlight the necessity of long-term programs based on sound research. Our method is designed to help achieve efficient results and to understand the response of the mangroves in this area to the impacts and actions of ecological restoration, from the biogeochemical-physiological level to the ecosystem and landscape level.

such as organic matter production and recycling. These forcing functions are referred to as the “environmental signature” of the ecosystem; and along with biological interactions, they shape ecological processes in mangroves, such as productivity, biomass

production, succession, litter dynamics, nutrient cycling, and sedimentation, favoring mangrove colonization and development and assisting the regeneration of mangrove forests. This requires planning at large scales, since these forcing functions are related to

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