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ENVIRONMENTAL CHARACTERISTICS OF MANGROVES FOR RESTORATION IN THE YUCATAN PENINSULA, MEXICO

Toyohiko Miyagi
Tohoku Gakuin University

SILVICULTURE MANUAL FOR MANGROVE RESTORATION IN THE YUCATAN PENINSULA, MEXICO

Koichi Tsuruda
Action for Mangrove Reforestation (ACTMANG)

March 2013

Tohoku Gakuin University
Action for Mangrove Reforestation (ACTMANG)
Japan International Cooperation Agency (JICA)
United Mexican States Ministry of the Environment
International Society for Mangrove Ecosystems (ISME)

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Cover photo: Ria Celestun, Yucatan Peninsula, Mexico by T. Miyagi

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Referencing: Citations in the text should be in chronological order by the author and date and are not numbered. All citations must be listed in the references at the end of the paper, with the names of authors arranged alphabetically. References should use the Harvard Referencing Style and abbreviations should conform to those of the BIOSIS Database.

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Illustrations: Photos and drawings should be submitted separately in JPG file, of suitable quality and form for direct reproduction.

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Environmental Characteristics or Mangroves for Restoration in the Yucatan Peninsula, Mexico

Silviculture Manual for Mangrove Restoration in the Yucatan Peninsula, Mexico

Environmental Characteristics of Mangroves for Restoration in the Yucatan Peninsula, Mexico

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Key words: Mangroves, restoration, rehabilitation, planting, Yucatan Peninsula, Mexico

1. Introduction

The Coastal Wetland Conservation Program was implemented in the Ria Celestun National Biosphere Reserve in the Yucatan Peninsula of Mexico from March 2003 to February 2008 (Appendix I). The program was a collaboration between the United Mexican States Ministry of the Environment and the Japan International Cooperation Agency (JICA). The overall goal of the program was improved conservation of Ria Celestun. Objectives were:

- Promotion of mangrove ecosystem restoration
- Sustainable use of natural resources by community-based organizations
- Improved solid waste management
- Establishment of information sharing about wetland conservation among relevant organizations and local communities is established
- Enhanced knowledge of local communities on the importance of Ria Celestun through environmental education

Silviculture Manual for Mangrove Restoration in the Yucatan Peninsula, Mexico written by Koichi Tsuruda is an output of the Mangrove Environment Rehabilitation Project, which formed part of the Coastal Wetland Conservation Program. It was based on knowledge gained and results from the field research conducted for the project by mangrove experts from Tohoku Gakuin University and Action for Mangrove Reforestation (ACTMANG). The field experience of JICA and the International Society for Mangrove Ecosystems (ISME) was incorporated.

That manual aims to guide efforts for carrying out rehabilitation of degraded mangrove environments and for restoration of mangrove forests in arid and semi-arid areas, which are widely distributed in the Yucatan Peninsula. In arid and semi-arid areas it is not always easy to restore mangrove forests to a state of high productivity. Where terrestrial vegetation is poor or non-existent coastal mangroves play an important role to provide local forest resources, fodder, landscape greenery, fish nursery and breeding ground, coastal protection and buffer from salt damage.

Also the manual is intended for foresters and field technicians in semi-arid areas who have actually seen the environmental deterioration and will be conducting a series of restoration efforts.

This paper consists of two parts: the first part describes the basic information about mangrove ecosystems to understand their actual condition; and the second part compiles key points and indicators that are necessary for judging and decision making for site selection to replant and rebuild the hydrological environment. In addition, techniques and knowledge necessary for nursery production, monitoring and evaluation are included.

2. Mangroves of the Yucatan Peninsula

2.1 Environmental Characteristics

The Yucatan Peninsula has a unique environment. Dry and wet seasons are distinct, the low flat land consists of limestone, which has high permeability, and there are no rivers. Due to the lack of freshwater supply from rivers, the wetlands easily dry up during the dry season.

Based on the average monthly temperature and rainfall chart of Merida City (Figure 2.1), it is important

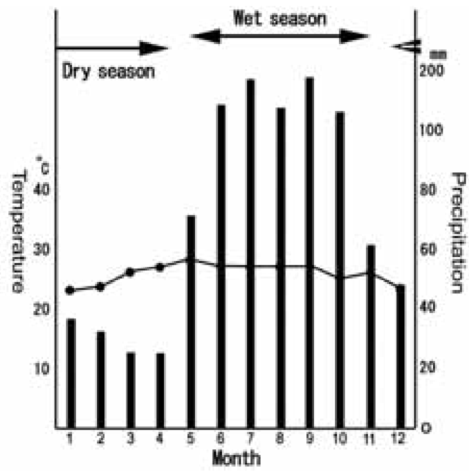

Figure 2.1 Average monthly temperature (line) and rainfall (bar) of Merida City, Mexico

to note the position of the rainfall bars relative to the temperature line. The wet season corresponds to where rainfall is above the temperature line and the dry season below. In Merida City, from May to November is the wet season and from December to April is the dry season.

The geographical and hydrological features of the west coast of the Yucatan Peninsula (Figure 2.2) are of the dryland type where evaporation exceeds precipitation. Salt is deposited on the mudflats, chaparro and inter-chenier habitats. Though there is a lack of surface water due to highly porous limestone deposits, abundant underground water and gently sloping aquifers distribute widely throughout the coastal regions of the Gulf of Mexico. Due to this topography, cenotes and springs commonly occur, and artesian ground water is discharged into the sea.

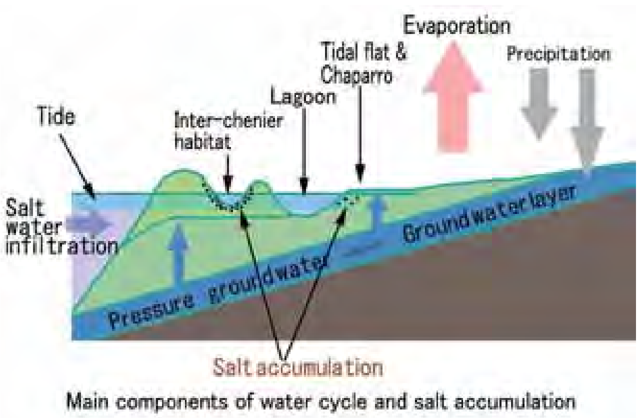

Figure 2.2 Geographical and hydrological features of the west coast of the Yucatan Peninsula

2.2 Major Mangrove Species

Four major mangrove species are found in the Yucatan Peninsula. They are *Rhizophora mangle* (Rhizophoraceae), *Avicennia germinans* (Avicenniaceae), *Laguncularia racemosa* (Combretaceae) and *Conocarpus erectus* (Combretaceae) (Figure 2.3).

Rhizophora mangle or red mangrove is a small to medium-sized tree of 10–20 m in height. Its most characteristic feature is the conspicuous, branched and arching, stilt or prop roots, which may spread so profusely. Leaves are opposite, simple, entire, and smooth with a prominent midrib. They are leathery, dark green, shiny above and lighter green below. Flowers are pale yellowish or cream coloured with four petals. They are borne on stalks in clusters of two or more buds. The fruit is an elongate greenish capsule. Hypocotyls are narrowly cylindrical, elongate, green with irregular small brown lenticels and distinct brown distal tips (Figure 2.4). The species often dominates the seaward side of mangrove forests, where it may form monospecific stands. Farther inland, it is mixed with other mangrove species. (Tiner, 1993; Allen, 2002; Duke & Allen, 2006)

Avicennia germinans or black mangrove is a small tree of 14–15 m in height. Leaves are simple, opposite and ovate with a blunt apex. Its lower surface is greyish-green while its upper surface is dark green. Both surfaces frequently show abundant salt crystals. Flowers are borne on terminal or lateral panicles. The corolla is white, yellowish at the base. Fruits are two-valved flattened capsules with a persistent calyx. Seeds are ovoid, flattened and covered with silky yellowish hairs (Figure 2.4). The bark is thick and grey, and the crown is small and rounded. The species is physiologically adapted to grow in soils flooded with seawater. (Tomlinson, 1980; Garibaldi, 2002)

Laguncularia racemosa or white mangrove is a moderately fast-growing, small, and often multi-stemmed tree that grows up to 15 m in height. Leaves are opposite, leathery, slightly fleshy, elliptic, rounded at both ends, dull yellowish-green on both sides and borne on reddish stalks with two raised gland dots near the apex. Flowers are small, numerous, stalkless, bell-shaped, whitish and borne in terminal and lateral clusters. The species is functionally dioecious, with trees having only male or both male and perfect flowers. Fruits are clustered, velvety greyish-green, slightly pear-shaped, flattened and ridged. (Little & Wadsworth, 1964; Tomlinson, 1980; Allen, 2002)

Conocarpus erectus or button mangrove is a small tree with rough and fissured bark. Leaves are ovate-lanceolate, spirally arranged and clustered distally. Petioles are short with a pair of circular glands on either side. The species is dioecious with trees having male and female flowers. Flowers are borne on terminal globose heads. Fruits are a laterally compressed nut bearing small angular seeds. (Tomlinson, 1980)

2.3 Mangrove Forest Types

Aerial photographs and general views of the various mangrove forest types in the Yucatan Peninsula are shown in Figure 2.5.

2.3.1 Fringe mangroves

Fringe mangroves typically develop along the shores of large coastal lagoons in the Yucatan Peninsula. With tidal water exchange from the lagoons, fringe mangrove forests are healthy in Ria Celestun. The forest mainly consists of *Rhizophora mangle* intermixed with *Laguncularia racemosa* and *Avicennia germinans*. Tall trees reach 20 m. Sediments on the forest floor consist of rich organic matter including

Rhizophora mangle

Avicennia germinans

Laguncularia racemosa (photo by M. Kainuma)

Conocarpus erectus (photo by M. Kainuma)

Figure 2.3 Major mangrove species in Yucatan Peninsula

Figure 2.4 Propagules of *Rhizophora mangle* (left) and seeds of *Avicennia germinans* (right) (photos by K. Tsuruda)

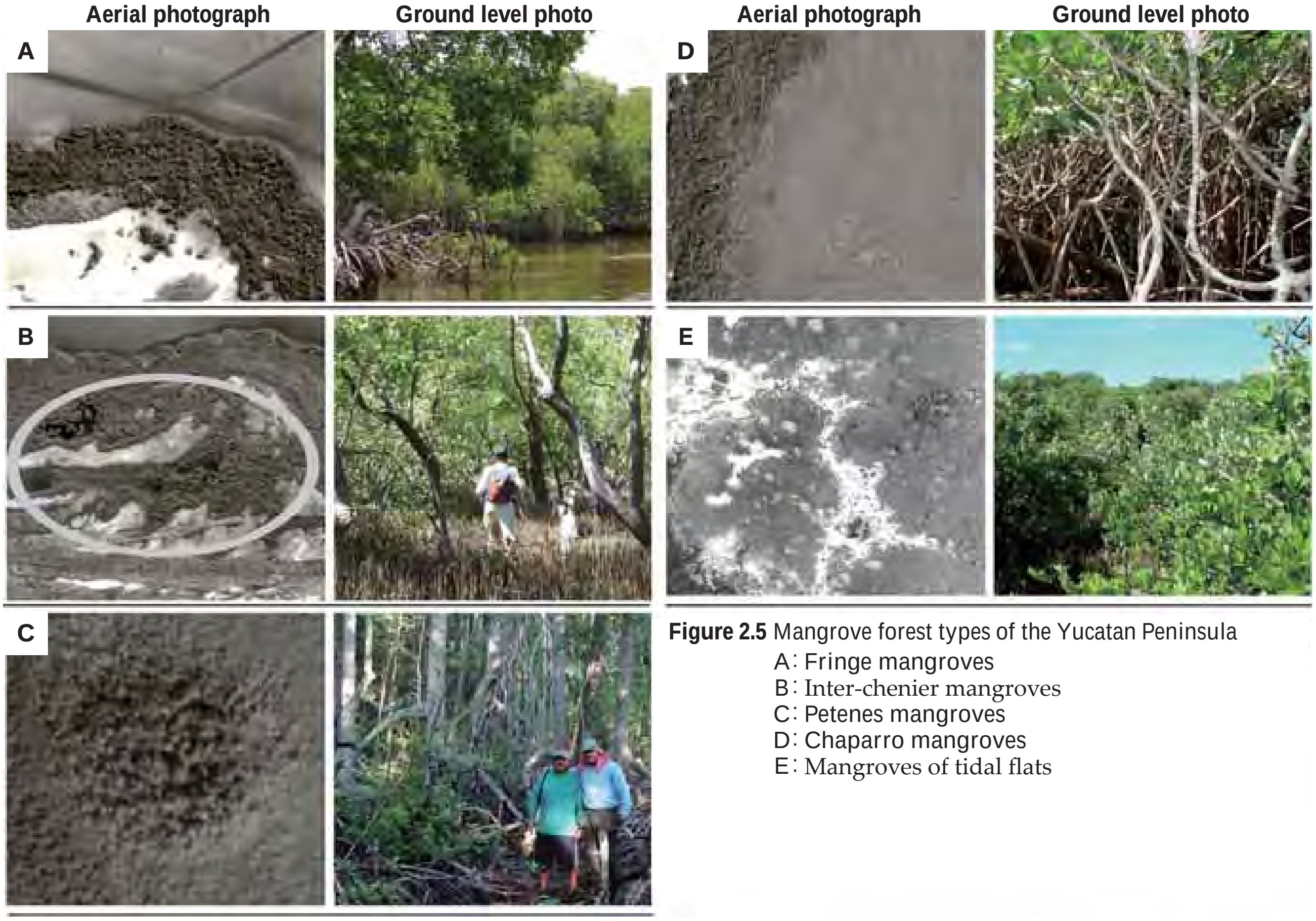

Figure 2.5 Mangrove forest types of the Yucatan Peninsula
A: Fringe mangroves
B: Inter-chenier mangroves
C: Petenes mangroves
D: Chaparro mangroves
E: Mangroves of tidal flats

silt and clay and peat. Sedimentation depth of these mangroves is less than 2 m.

2.3.2 Inter-chenier mangroves

In Ria Celestun, villages are located on large beach ridges made up of a number of divergent small sand bars that wind towards the lagoons. Inter-chenier mangroves grow at the low ground level of these sand bars and are separated from the lagoon by fringe type of mangroves. *Avicennia germinans* is the major constituent of the mangroves forest interspersed with *Rhizophora mangle* and *Laguncularia racemosa*. The tree height is no more than 10 m but some tall trees can reach up to 20 m. Water exchange is limited inside these inter-chenier wetland. Sediments consist mainly of sand where seawater can easily penetrate. During the dry season, strong evaporation causes soil salinity to become very high.

2.3.3 Petenes mangroves

Petenes mangroves along the coasts of the Gulf of Mexico are recharged by underground water. Mangroves grow in concentric circles or domes. The shape varies depending on the soil salt concentration. In the center, mixed forests dominated by *Rhizophora mangle* and *Laguncularia racemosa* reach up to 25 m and are associated with freshwater vegetation such as palms and lilies. At the periphery, tree height becomes shorter with *Avicennia germinans* (pioneer species) replacing *Rhizophora mangle*. Sediments often consist of non-degraded peat in the center where the ground level is slightly higher. Due to high freshwater content, small fauna such as frogs, cockroaches, spiders and scorpions are frequently seen.

2.3.4 Chaparro mangroves

In many locations, large areas of dwarf or chaparro mangrove forest are seen landward of fringe mangroves. Tree height is only 2 m and rarely 3 m. They form dense bushes comprising purely of *Rhizophora mangle* trees with main trunks not easily recognized. Reproduction is mainly vegetative as the trees are growing under high salt stress. Trees are gnarled with crooked trunks having diameter at breast height (dbh) of less than 5 cm. Sediments consist mainly of non-degraded peat derived from fine roots of *Rhizophora mangle*.

2.3.5 Mangroves of tidal flats

Tidal flat mangroves grow where the aggradation of sediments in large lagoons develops to form an intertidal zone between the middle and high water levels. These are mainly dense or sparse *Avicennia* and *Rhizophora* dwarf forests. Tree height is generally short, and in the case of *Rhizophora* forests, there is a tendency for trees to produce a high density of stilt roots. The trees are likely to be under salt stress due to surface water cut off. Sediments consist mainly of mangrove peat but sometimes fine clay or silt.

2.4 Mangrove Growth Levels

In Ria Celestun, it is possible to categorize mangroves based on growth levels, forest structure and tree mortality. We identified seven categories of forests of *Avicennia germinans*, *Rhizophora mangle* and *Laguncularia racemosa* in Ria Celestun. Levels 0 and 1 refer to dead or dying forest while levels 5 and 6 refer to good and tall forest, respectively (Figure 2.6).

We then surveyed the soil salinity at root depth in the various categories of forests. By plotting the data, we were able to identify the relationship of soil salinity causing mortality for each species (Figure 2.7). From the figure, the following relationship between the soil salinity and growth level was understood:

- Overall, there is a clear relationship between soil salinity and mangrove growth level. When the salinity is higher than 5%, the mangroves start to die (level 1). At 7% salinity and above, dead forest (level 0) is observed.
- The dwarf mangrove forest at level 3 can be an extension of dense low bush up to 7% soil salinity. Some mangroves can grow even higher salinity. It is likely that this may be due to local differences.
- *Avicennia germinans* has a tendency to show a higher salt tolerance than *Rhizophora mangle*. *Laguncularia racemosa* grows well at low salinity (below 3%).

2.5 Mangrove Hydrological Cycle

2.5.1 Tidal flat mangrove habitat

The hydrology of a tidal flat or chaparro mangrove habitat (Figure 2.8) is significantly more favorable than the adjacent inter-chenier mangrove habitat. The key factors influencing this mangrove habitat are freshwater supply from the inland and rainfall, availability of saline water through tides and aquifers, and evaporation during the wet and dry seasons. Under these natural conditions, mangrove forests develop.

Growth level	Forest type, structure and mortality	Illustration of forest type based on growth level, structure and mortality
6	**Tall forest** Tree height > 20 m Mortality rate < 5%	
5	**Good forest** Tree height > 10 m Mortality rate < 5%	
4	**Dense scrub forest** Tree height < 10 m Closed canopy	
3	**Sparse scrub forest** Tree height < 5 m Trees scattered Mortality rate < 20%	
2	**Chaparro forest** Tree height < 2 m Dense dwarf forest Main trunk not clear Mortality rate < 20%	
1	**Nearly dead forest** Mortality rate up to 90% Regeneration rare	
0	**Dead forest** Almost 100% mortality Regeneration none	

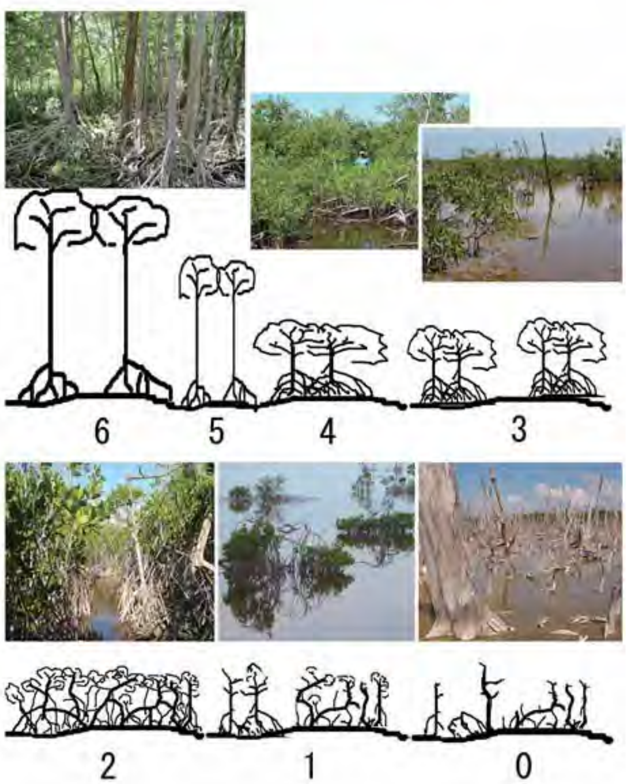

Figure 2.6 Categorization of mangrove forest types based on growth levels, structure and mortality in the Yucatan Peninsula

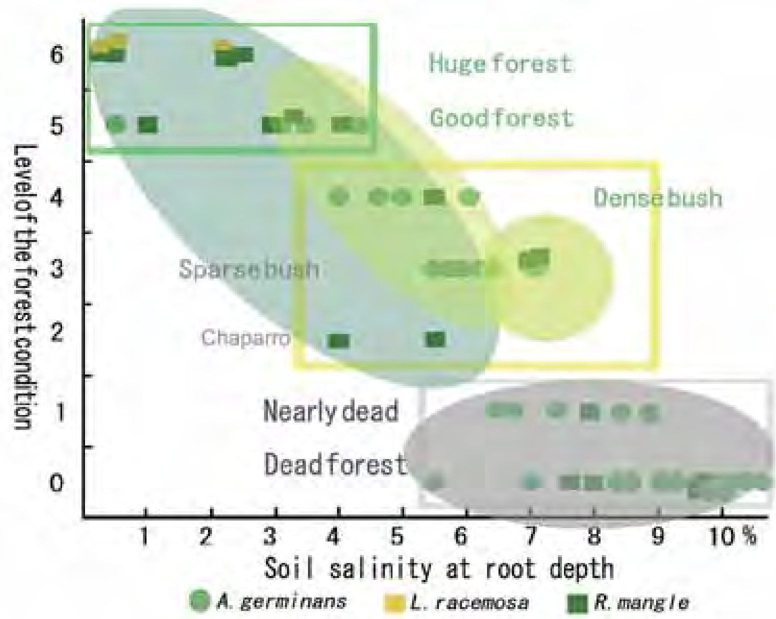

Figure 2.7 Relationship between forest types and soil salinity at root depth

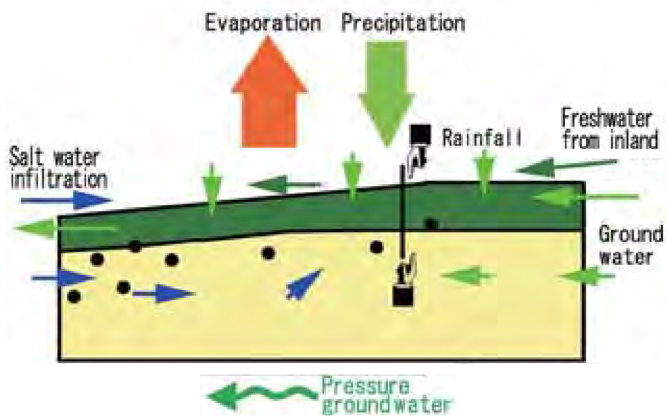

Figure 2.8 An illustrated model of the geomorphology, hydrological cycle and salt accumulation in a tidal flat or chaparro mangrove habitat

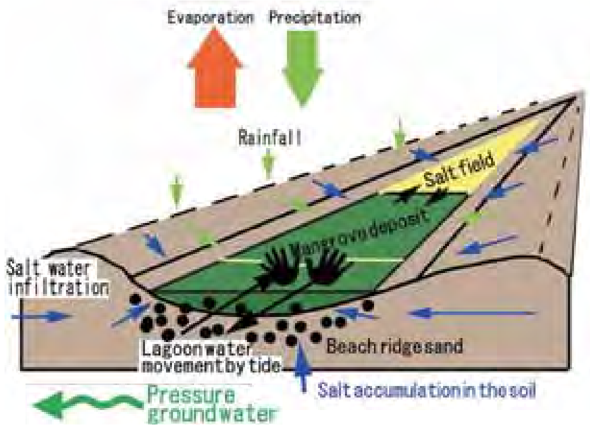

Figure 2.9 An illustrated model of micro-topography, hydrological cycle and salt accumulation in an inter-chenier mangrove habitat

Dwarf or low-stand chaparro mangroves grow where salt stress is strong, and where fresh water supply is available, healthy mangroves grow. The hydrological cycle is water movement received both from the land and the sea. Therefore, inhibiting water movement, e.g. by road construction, will result in high salt accumulation for mangroves at the seaward and landward side of the road due to obstruction in water exchange and evaporation, eventually leading to death of trees.

2.5.2 Inter-chenier mangrove habitat

The hydrological cycle of the inter-chenier mangrove habitat is illustrated in Figure 2.9. A high amount of salt accumulates in the soil at the lower ground levels. For this reason, Celestun has the oldest salt pans in Mexico. The key features of this habitat in terms of water cycle are the wet and dry seasons, the presence of beach ridges consisting of water-permeable sand deposits, and the lack of freshwater supply from the land and water exchange with lagoons. In this topography, it is more difficult to exchange water from lagoons, which leads to high evaporation. Saltwater from the sea accumulates just below the ground surface through evaporation. This process is the same as the accumulation of calcium sulphate or salt in desert soil.

In Celestun, salt that accumulates during the dry season supports the development of a salt industry. Near the lagoon, soil salinity is reduced through water exchange and these sites enable the maintenance of healthy mangrove forests. In these sites, development activities that impede water exchange from the lagoon would lead to the creation of salt pans and consequently death of the mangrove forest.

3. Mangrove Forest Conditions

3.1 Indicators of Forest Deterioration

In the semi-arid coastal areas of the Yucatan Peninsula, environmental stress leading to the death of mangrove forests can either progress slowly or quickly. Such deterioration can be monitored with respect to tree health, forest condition and topography. Other indicators include susceptibility to insect herbivory and hurricane damage.

3.1.1 Tree death

Deterioration of trees can be seen more clearly in *Avicennia germinans*. The levels and types of deterioration of the species are illustrated in Figure 3.1.

1. In healthy trees of *Avicennia germinans*, the main trunk is slightly bent. Leaves borne on branches are green and dense, and pneumatophores are yellow-green to light green.

2. Tree vigor declines when the tree form is changed by the death of main branches with fewer leaves.

3. Peripheral ends start to die showing symptoms of die-back. Leaves turn yellow and start to undergo necrosis.

4. All the peripheral ends and leaves die (severe die-back).

5. The tree dies leading to mortality of the entire forest stand.

6. As pneumatophores grow, there is some root-death but as the deterioration progresses, the rate of root death exceeds growth. Exposure of cable-roots due to erosion also facilitates tree death. Under stress, the roots show symptoms of white fungal infections.

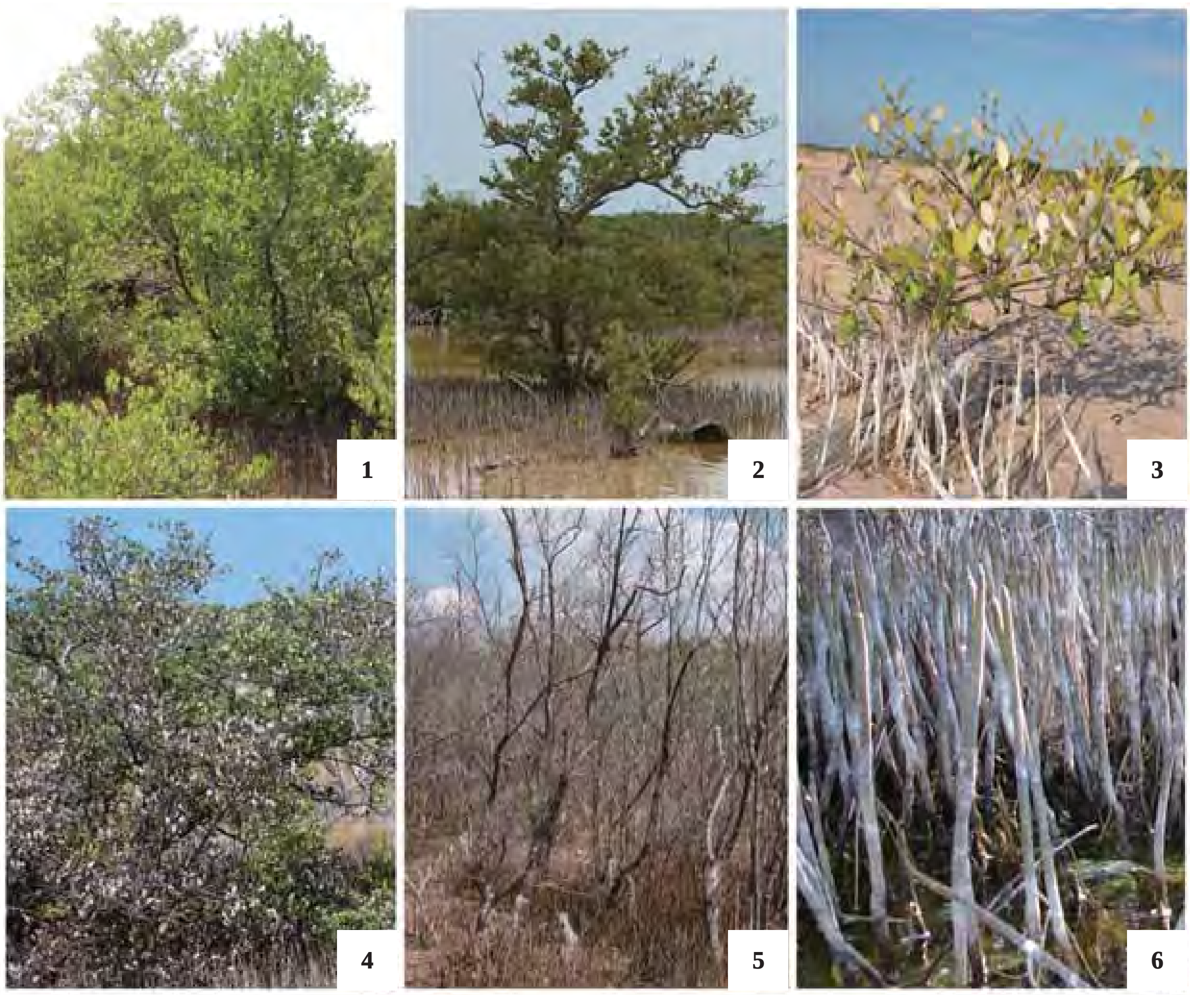

Figure 3.1 Characteristics of tree deterioration in *Avicennia germinans*

3.1.2 Forest death

Forests of *Rhizophora mangle* are more susceptible to environmental stress. The levels and types of forest deterioration of the species are illustrated in Figure 3.2.

1. Trees of *Rhizophora mangle* in a large mangrove forest area start to die in a wave-like pattern.

2. Closer view of mangrove death in wave-like pattern. In this case, the dead forest area is progressing gradually. The cause is not clear but it can be due to increase of soil salinity caused by change in the topography or to insect herbivory.

3. Wide area of forest death is preceded by an increase in soil salinity or long-term inundation of pneumatophores during the wet season.

4. Death of young trees at the edge of the forest. The likely cause is high salinity near the forest edge and pneumatophores choked by sludge.

5. The whole mangrove stand is dead as high soil salinity reaches the root depth.

6. Ten years after forest death and only decomposing stumps remain.

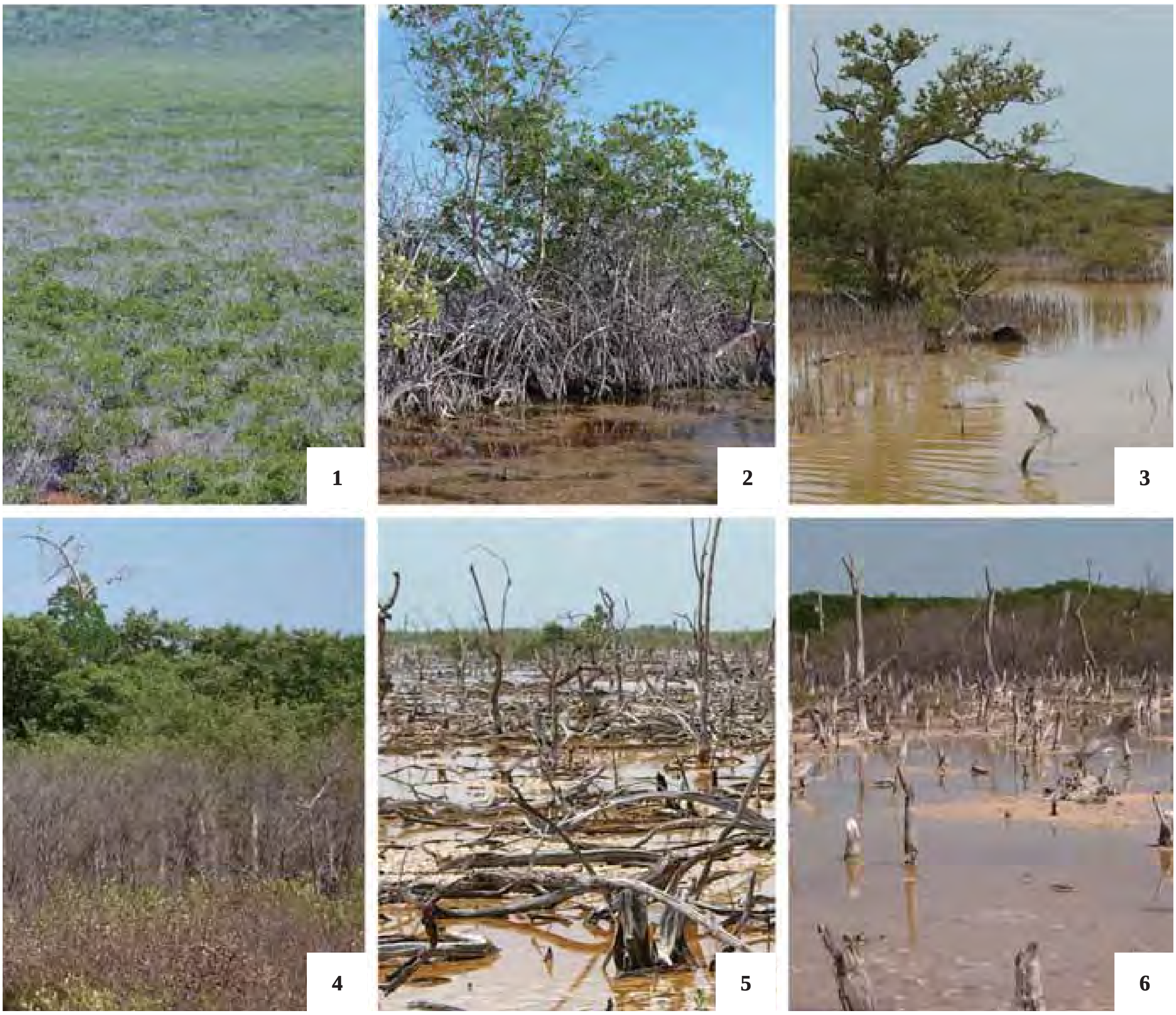

Figure 3.2 Categories of dying or dead *Rhizophora mangle* forests

3.1.3 Environmental deterioration

Many stresses to mangroves in semi-arid areas are caused by environmental deterioration. The various categories of environmental deterioration of mangrove forests are shown in Figure 3.3.

1. When much freshwater stagnates during the rainy season, pneumatophores of *Avicennia germinans* become inundated, choking the plants.

2. When tidal water is cut off during the dry season, soil salinity increase through active evaporation resulting in mangrove death.

3. Organic matter decomposes at the floor of dead forests and becomes sludge. The runoff and accumulation of sludge leads to formation of gullies in which water may stagnate.

4. When sludge accumulates on the forest floor, a portion may runoff to the forest edge during the rainy season.

5. Top 3 cm of forest soil consists of non-degraded peat in the process of becoming sludge.

6. Sludge from dead forests is exported out to the forest edge by slow water flow that may cover pneumatophores or suppress water movement.

7. Thick accumulation of sludge is formed.

8. Sludge accumulates over the non-degraded peat (top 18 cm).

9. In this area, salt pans and culture ponds of *Artemia salina* (brine shrimp) generate highly saline water.

10. A culture pond of brine shrimp in the process of drying up.

11. To produce salt, highly saline water is drained from salt pans to the surrounding environment.

12. Road construction prevents natural water exchange and leads to deterioration of the mangrove environment.

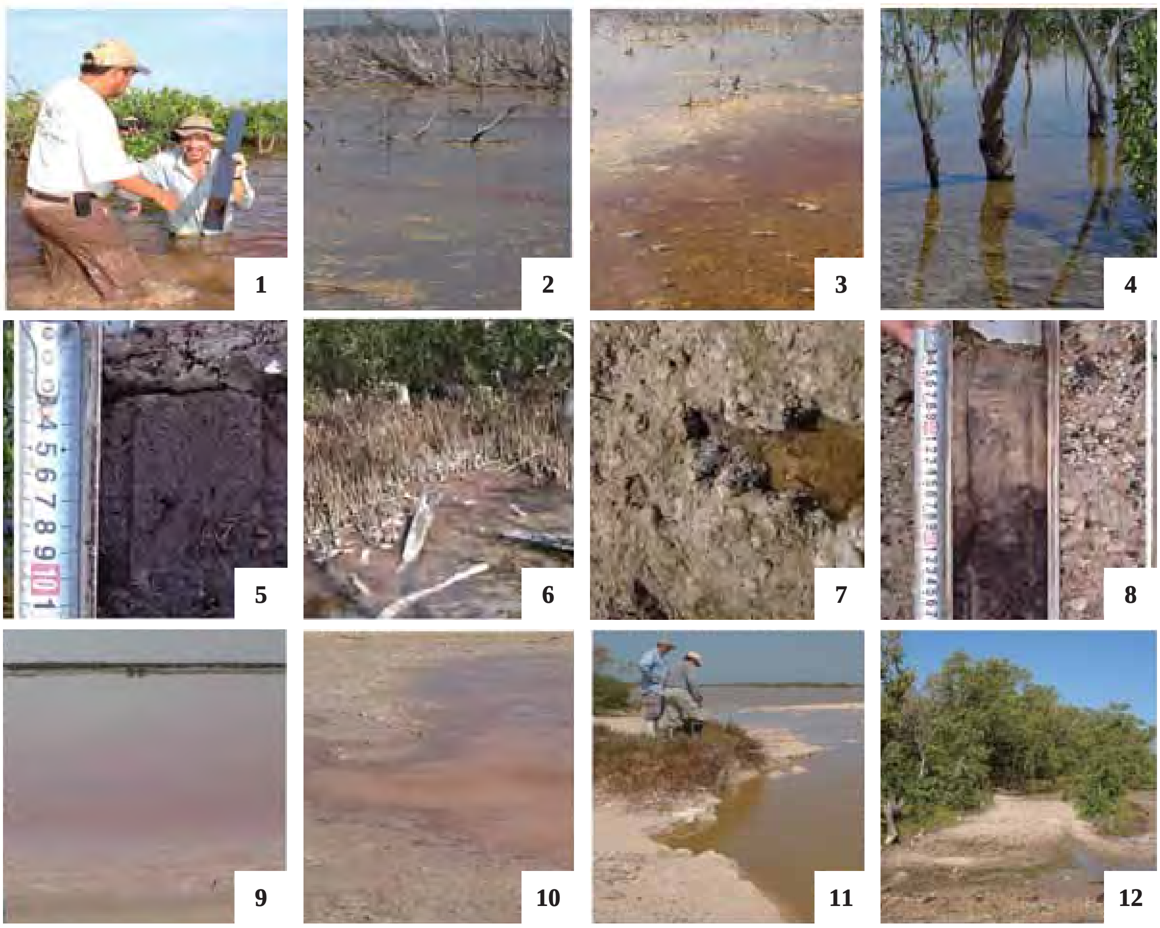

Figure 3.3 Categories of environmental deterioration of mangrove forests

3.2 Case Studies

3.2.1 Block C in Celestun

Block C in Celestun is a degraded inter-chenier mangrove forest of 1.5 ha. Environmental data based on site characteristics are shown in Figure 3.4. An aerial photograph and proposed mangrove rehabilitation scheme is shown in Figure 3.5.

Land evaluation factors	Possible range for growth
Ground level	HH H M L LL
Surface water salinity	>6.5 6 5 4 <4
Soil salinity	>6.5 6 5 4 <4
Soil material	Clay Loamy clay Silt to Sand
Vegetation level on site	D ND SB DB Go
Forest level in surroundings	D ND SB DB Go
Tidal water frequency	Indirect Seldom Frequent
Stagnation depth of freshwater in rainy season	>30 30-20 20-10 <10

Rhizophora mangle *Avicennia germinans*

Figure 3.4 Some environmental data of Block C in Celestun

Ground level: HH: highest high water level, H: mean high water level, M: mean water level, L: mean low water level, LL: lowest low water level

Surface water salinity: Measuring salinity of above ground water (%)

Soil salinity: Measuring free water at the depth of root development (%)

Vegetation level in sites and forest health level in the surroundings: D: dead forest, ND: nearly dead forest, SB: sparse bush, DB: dense bush, GO: good forest.

Tidal water frequency: Tide frequency should be checked independent of the ground water level. Inundation time is easily affected by change in topography especially in the micro-tidal areas.

Depth of stagnated freshwater in the rainy season (mm): The measurement should be taken at the middle of the rainy season. The micro-relief is variable and multiple sampling points are necessary to ensure the accuracy of data.

The advantage of selecting Block C as a restoration site is the suitable ground level, soil condition and existence of an access road. There are healthy mangrove forest stands next to the area. On the other hand, disadvantages are frequent submergence during the wet season, minimal tidal action, high soil salinity, and the drying out of the land during the dry season.

The above mentioned disadvantages are attributed to the loss of tidal regime. It is necessary to secure proper water exchange by recovering tidal flow. However, the accumulated salts in soil cannot be reduced only by surface recovery but may initially require the digging of an infiltration well.

One of the major causes of the loss of tidal flow at this site is the accumulation of sludge at the forest edge, which functions as a dike. Fortunately, a lagoon within the adjacent mangrove forest has good tidal exchange. Therefore, it was suggested to connect the lagoon to the restoration site with a canal to provide the tidal water into the site. Although the frequency of incoming tide will depend on the base level of the canal, it occurs once every few days since the ground level of the restoration site is not high. During the spring tide, water flow will enter into the entire restoration site. Construction of trenches and mounds would also facilitate water flow into the site.

3.2.2 Block A in Celestun

Block A in Celestun is a degraded mangrove forest of the inter-chenier type. It has dead *Avicennia* mangroves beside the beach ridge and fringing *Rhizophora* mangroves bordering a lagoon (Figure 3.6). The ground height is favorable but the soil salinity is extremely high (10%). During the wet season,

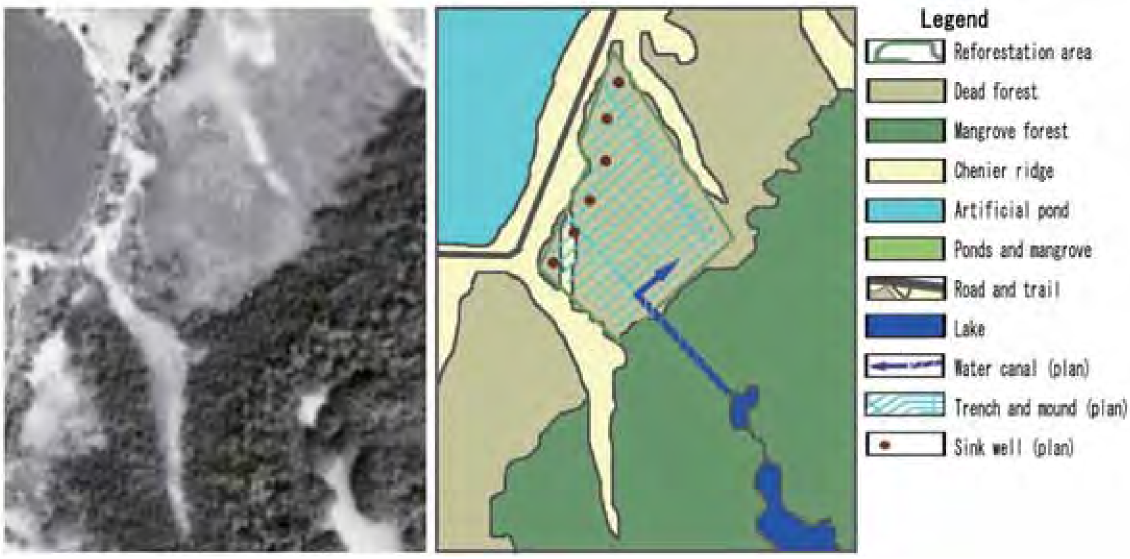

Figure 3.5 An aerial photograph (left) and proposed mangrove rehabilitation scheme (right) of Block C in Celestun

mangrove roots are inundated by stagnant water and during the dry season, the ground surface dries out. Tidal water rarely reaches this area. The major reason for forest mortality is the lack of water exchange from the lagoon and the soil is highly saline. To restore such a condition, it is necessary to reduce the soil salinity to below 6% and to promote water exchange from the lagoon.

3.2.3 Plot 4 in Isla Arena

Plot 4 in Isla Arena is a degraded *Avicennia* forest (Figure 3.7). Some environmental data are shown in Figure 3.8.

There are several thousand hectares of dead *Avicennia* forests in Isla Arena and they are continuously expanding. The main reason for mangrove loss is the construction of a road parallel to the coastline, which prevented freshwater supply from the landward side and increased soil salinity during the dry season (Figure 3.9). The road construction generated sludge from surface organic matter, which moved into the seaward side and inhibited tidal water exchange.

After the construction of a canal at the road, there was freshwater supply from the landward side. However, inundation of pneumatophores during the wet season further promoted forest mortality which had already been suffering from salt stress. The area of dead forest has been expanding. However, Plot 4 showed slight forest recovery and was chosen as one of the sites for rehabilitation.

Compared to other areas in Isla Arena, the advantage of Plot 4 as a mangrove rehabilitation site was the relatively

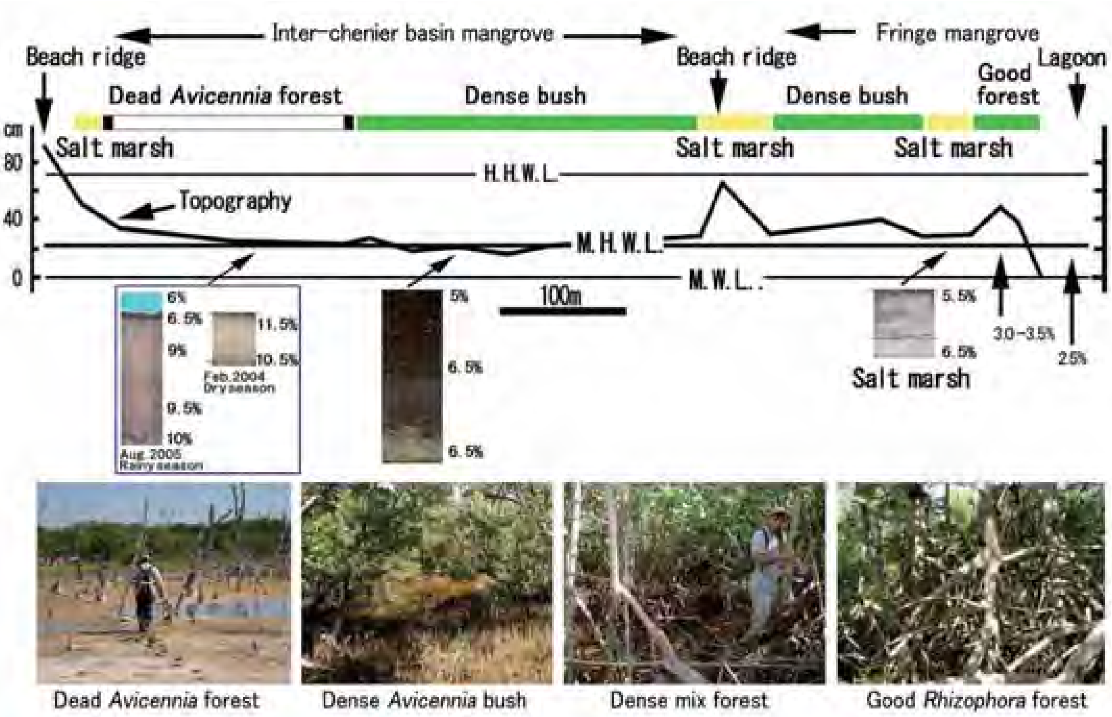

Figure 3.6 Cross-section data of the topography, soil and vegetation of Block A in Celestun

Figure 3.7 Degraded *Avicennia* forest of Plot 4 in Isla Arena

Land evaluation factors	Possible range for growth
Ground level	HH H M L LL
Surface water salinity	>6.5 6 5 4 <4
Soil salinity	>6.5 6 5 4 <4
Soil material	Clay Loamy clay Silt to Sand
Vegetation level on site	D ND SB DB Go
Forest level in surroundings	D ND SB DB Go
Tidal water frequency	Indirect Seldom Frequent
Stagnation depth of freshwater in rainy season	>30 30-20 20-10 <10

Rhizophora mangle *Avicennia germinans*

Figure 3.8 Some environmental data of Plot 4 in Isla Arena (See abbreviations in Figure 3.4)

low surface and soil salinity. Although the vegetation is extremely sparse, there still some mangrove bushes in the area. In addition, the presence of a water gate and good accessibility by road are further advantages.

Disadvantages of Plot 4 are almost no tidal flow and the good tidal environment is 2 km away. In addition, the topography experiences 10–30 cm depth of inundation during the wet season. However, there is a tendency for recovery and patchy mangroves are recognized. Therefore, this project site is at the border line of mangrove recovery or death.

We mapped the mangrove vegetation in Plot 4 (Figure 3.10). The map showed that seedlings, saplings and trees of *Avicennia germinans* and *Rhizophora mangle* grew on very restricted ground level. The height difference with the adjacent low ground was only 15–20 cm but it is obvious that this difference is the inundation depth difference. The density of adult, saplings and seedlings confined to the higher ground level was 506, 1133 and 1122 per hectare, respectively. No growth was observed at the ground level 10 cm or lower.

Based on the data obtained, it is recommended to plant seeds, propagules or potted seedlings to expand the patchy mangroves at slightly elevated ground level. It is hoped that these patches of mangroves would gradually expand the total mangrove forest area.

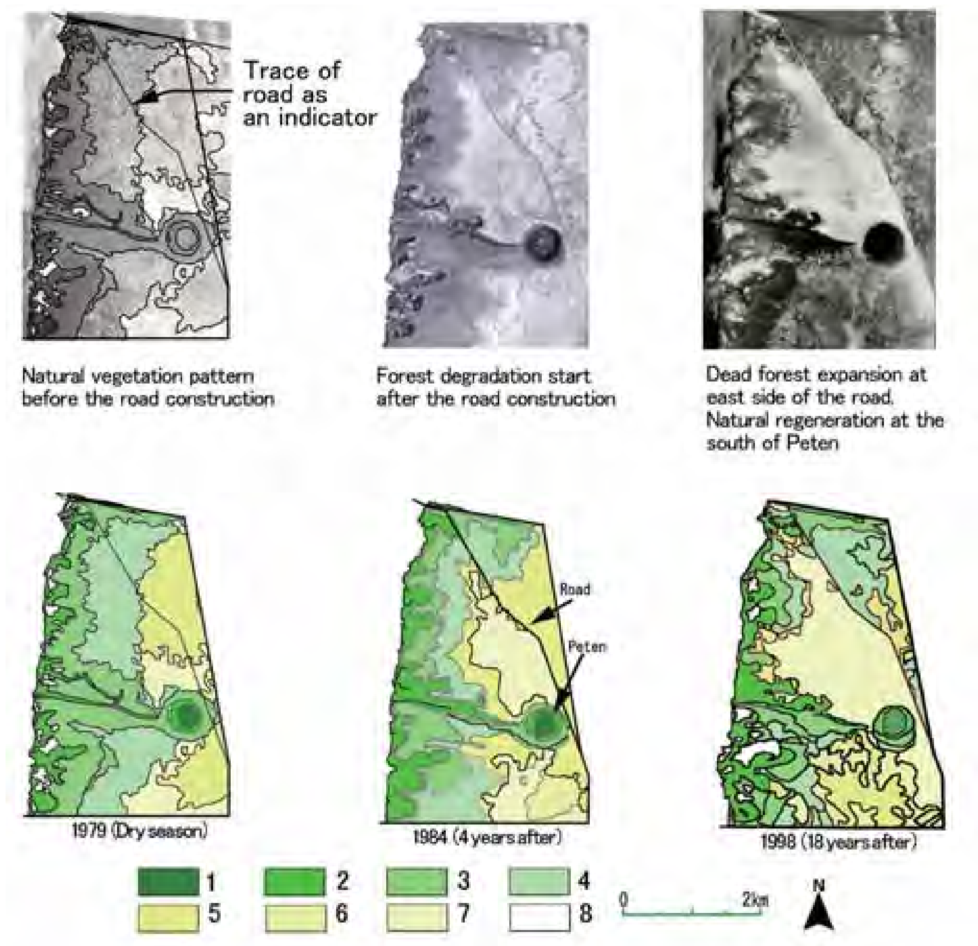

Figure 3.9 Photographic interpretation of changes in the distribution of mangrove forest in Isla Arena following road construction
1: Huge forest at Peten, 2: Fringe good forest, 3: Dense bush, 4: Bush,
5: Sparse Chaparro forest, 6: Nearly dead forest, 7: Dead forest and salt marsh,
8: Cleared area

3.2.4 Plot 2 in Isla Arena

Based on the survey data of Plot 2 in Isla Arena (Figure 3.11), there is a good correlation between forest health, topography and soil salinity. The soil salinity reached a high level of 10% to the east side of the road. When freshwater supply from the land is cut off by the road, the soil salinity increased. Where trees died, the surface peat layer is converted to sludge, which moves to the forest edges, causing mortality to the mangrove vegetation. This is further aggravated by water stagnation during the wet season.

3.2.5 Summary

In all cases, the main strategy to restore the environment is to reduce soil salinity and inundation time by freshwater during the wet season. The most critical factor to recover is the tidal regime, the loss of which created all these problems. One should bear in mind that other factors may also be responsible for triggering environmental deterioration. In addition, the project areas must take into consideration not only natural factors but also other issues including land ownership, socio-economic aspects of resource utilization, accessibility of planting sites and proximity to nurseries.

4. Mangrove Rehabilitation Project

4.1 Planning and Implementing the Project

4.1.1 Understanding the causes of environmental deterioration

Environmental deterioration is often caused by a combination of factors. Sometimes even when the causes of forest death are identified, it is not always possible to restore a forest. For example, if the forest died due to high soil salinity, it may be difficult to dilute the high salt content. When environmental rehabilitation is planned, we need to take into consideration a variety of factors. Some of causes of environmental deterioration and decision making for rehabilitation are tabulated in Table 4.1. The process of decision making for rehabilitation of dead mangrove forest areas is illustrated in Appendix II.

4.1.2 Assessing the possibility of rehabilitation

Various site conditions that are suitable for the growth of *Avicennia germinans* and *Rhizophora mangle* are listed in Figure 4.1. These requirements need to be met when selecting sites for rehabilitation.

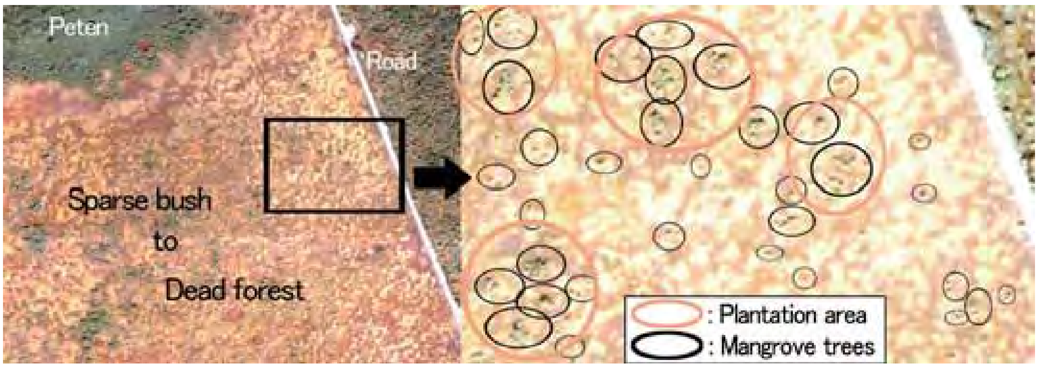

Figure 3.10 Mapping mangrove vegetation of Plot 4 in Isla Arena

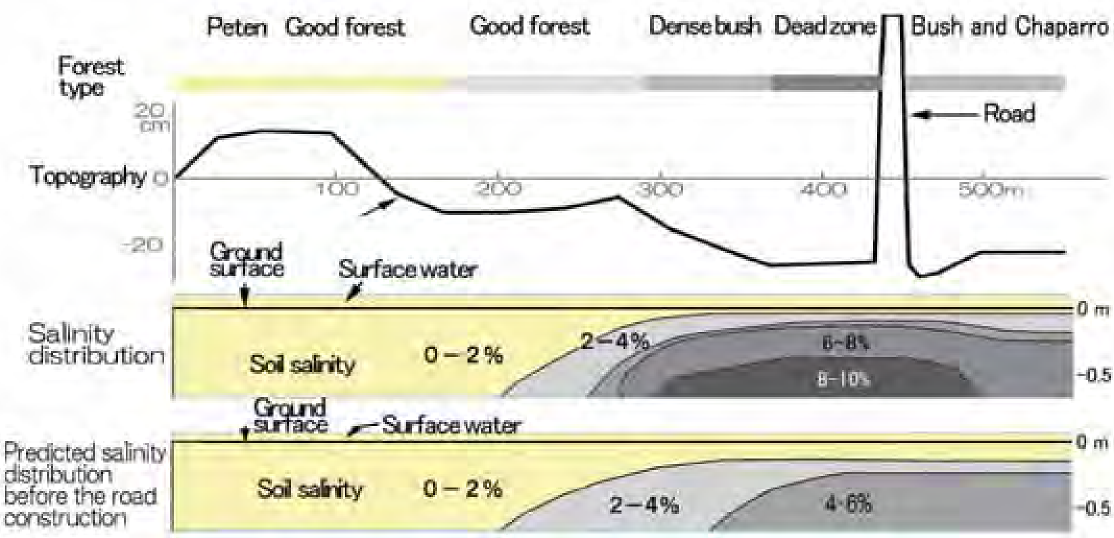

Figure 3.11 Cross-section data of the topography, soil and vegetation of Plot 2 in Isla Arena

Table 4.1 Causes of environmental deterioration and decision making for rehabilitation

Causes of forest mortality	• Pneumatophore inundation during rainy season • Flooding of highly saline water • Salt accumulation due to ground surface desiccation during dry season
Process and extent of forest death	• Submergence of pneumatophores lead to suffocation and tree death • Expansion of dead forest at the forest edge • Salt accumulation at mangrove root depth exceeding the growth limit of over 6%
Targets for problem solving	• Reduction of water level during wet season • Securing water exchange system • Dilution of soil and surface ground salt
Counter-measures	• Soil ploughing • Trenching and mounding • Canal construction between lagoon and the sea • Infiltration well construction and pump up the water from surface well

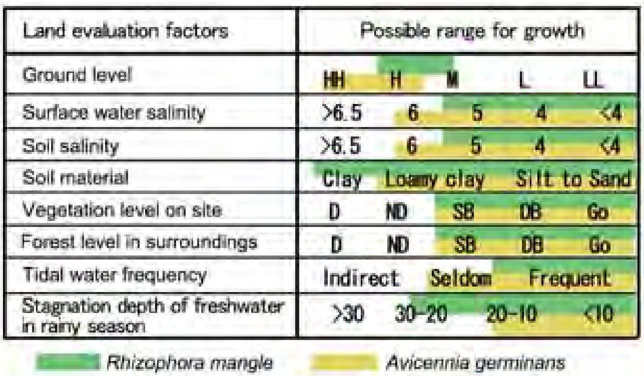

Figure 4.1 Sites conditions suitable for *Rhizophora mangle* and *Avicennia germinans* (See abbreviations in Figure 3.4)

4.1.3 Working with the local communities

When planning a mangrove rehabilitation project, it is vital to work with the local communities. We need to meet and explain our plans to land owners, local government and administrators, chiefs and heads of villages, and to receive their opinions, ideas, agreement and support. Information such as land use practices, boundaries, land ownership including management and utilization of resources is vital when selecting sites for planting, establishment of nurseries, areas for temporary storage for planting materials and their transportation accessibility. The employment of the local people in the implementation of the project activities would foster closer ties and greater support.

4.1.4 Optimizing the scheduling of project activities

When planning and implementing the project, it is essential to understand their work practice and annual work cycle. The weather with distinct wet and dry seasons affects work efficiency. Other factors would include the fruiting season of mangrove species, availability of local manpower and daily tidal regimes.

4.1.5 Nursery location and seedling transportation

When selecting the site for the nursery, the following criteria should be considered:

1. Relationship with the tidal level: It is better to establish a nursery in a tidal area since potted seedlings need daily irrigation.

2. Accessibility to the planting site: It is recommended that the nursery be located in proximity to the planting site as this would facilitate the transportation of potted seedlings.

4.1.6 Developing counter-measures

When planning and implementing the rehabilitation project, adverse environmental factors (both physical and biological) would be encountered and counter-measures need to be developed to enhance planting success (Table 4.2).

According to the JICA Bali mangrove plantation project (Inoue *et al*., 1999) and other mangrove plantation experiences, there are no known cases of mangrove plantations being destroyed by insects. Therefore, it is not necessary to take special precautions against insect damage.

4.2 Evaluation of Plantations

4.2.1 Developing the criteria for evaluation

The environment in the Yucatan Peninsula is not the type where *if you plant mangroves they will grow into a forest*. In such a harsh semi-arid environment, restoration of the tidal environment is the most important factor. Even so, much improvement of soil salinity cannot be expected. When evaluating mangrove plantation within a dead forest of semi-arid areas, we need to keep in mind that *the environment has improved to grow mangroves where it used to be a place of dying off*. Since the soil condition is not totally improved, it is difficult to obtain a high survival rate of planted seedlings.

Table 4.2 Adverse environmental factors that need counter-measures for mangrove planting

Factor	Damage	Counter-measure
Soft ground	Seedlings dislodged and fall over	Fasten seedlings to bamboo stakes for support. Re-schedule planting time or insert propagules deeper.
Wind	Seedlings blown away by strong wind	Fasten seedlings to bamboo stakes for support. Re-schedule planting time or insert propagules deeper.
Wave	Seedlings dislodged and washed away by waves	Fasten seedlings to bamboo stakes for support. Re-schedule planting time or insert propagules deeper.
Water flow	Soils at root level scoured by water flow and seedlings washed away	Fasten seedlings to bamboo stakes for support. Re-schedule planting time or insert propagules deeper.
Oil	Seedlings killed by attachment	Wash off oil with seawater.
Garbage	Seedlings tangled, causing them to die or be washed away	Fasten seedlings to bamboo stakes for support. Set-up protective fences.
Seaweed	Seedlings tangled, causing them to die or be washed away	Fasten seedlings to bamboo stakes for support. If seaweeds are found, set-up bamboo fences.
Barnacles	Seedlings infested, causing them to die or be washed away	Remove barnacles from infested seedlings.
Crabs	Propagules and seeds damaged by feeding	Currently no proper counter-measures against crab attack.
Insects	Leaves damaged by feeding	Wash off insects with seawater or remove by hand.

Maintaining a healthy tidal environment is a key to the success of mangrove plantations. In semi-arid areas such as the Yucatan Peninsula, a small change in topography alters the tidal environment, followed by changes in the soil condition. This will result in the death of mangroves. The success to rehabilitate the degraded mangroves depends on the restoring the tidal environment. The four key questions to ask when evaluating mangrove rehabilitation are:

1. How do the planted mangroves appear?
2. How has the tidal regime changed?
3. Is soil salinity at the root depth restored to that of seawater?
4. Is stagnation of water observed during the wet season?

4.2.2 Monitoring growth and survival

Even if the survival rate of first planting was 60%, it is a significant improvement and positive step towards the rehabilitation of dead mangrove forests. Instead of rushing to carry out supplementary planting, it would be best to monitor the growth performance and to determine the causes of mortality. Record the growth rate and any changes in survival rate for at least half a year or until the dry season ends.

The surviving seedlings under the restored tidal regime are highly valuable, as they are the ones that survived the dry season under high soil salinity. This survival rate should be counted as an environmental restoration result. Even if the rate was only 50% in the first year for seedlings planted in 0.5 and 1.0 m intervals, after few years a closed forest canopy can be observed.

It is not easy to restore a dead forest environment under hyper-saline soil condition. Various combinations of measures need to be undertaken. First, recover tidal flow environment and then check the survival rate of planted seedlings and monitor the gradual recovery in soil salinity. After these measures, improved planting activity can then be planned.

4.3 Assessment of Recovery

4.3.1 Chronological photographic monitoring

A useful method of assessing the growth and development of planted mangroves is to photograph them over time from the same distance and angle (chronological photographic monitoring). Under improved site conditions, the initial growth of planted mangroves is fast and can be clearly seen within six month to a year if the initial planting site is barren.

An example of a successful mangrove plantation in Celestun (Block A) is shown in Figure 4.2. The arrow indicates the only remnant tree of *Avicennia germinans* in the area which was about to die in March 2005. The second photo is taken six months after planting *Rhizophora mangle* and *Avicennia germinans* (October

2006), followed by yearly progress of the plantation until February 2010.

In early 2006, a waterway was constructed in Block A, Celestun, and the tidal environment restored (Figure 4.3). Initially, seeds of *Laguncularia racemosa* were dispersed into the plantation site by tide, and the species started to establish. Gradually, the planted species of *Rhizophora mangle* and *Avicennia germinans* started to grow. By 2010, the rehabilitated mangrove forest successfully established, resembling that of the natural forest type.

4.3.2 Assessing tidal flow recovery

Various engineering measures such as construction of canals and waterways, digging of sink and surface wells, and trenching and mounding has been tried (Figure 4.4). It is important that the local people are involved in these activities (Figure 4.5).

The cost-effectiveness of these measures which are aimed at restoring the tidal regime prior to plantation establishment needs to be determined. This can only be ascertained through regular monitoring of environmental parameters such as soil and water salinity (Figure 4.6).

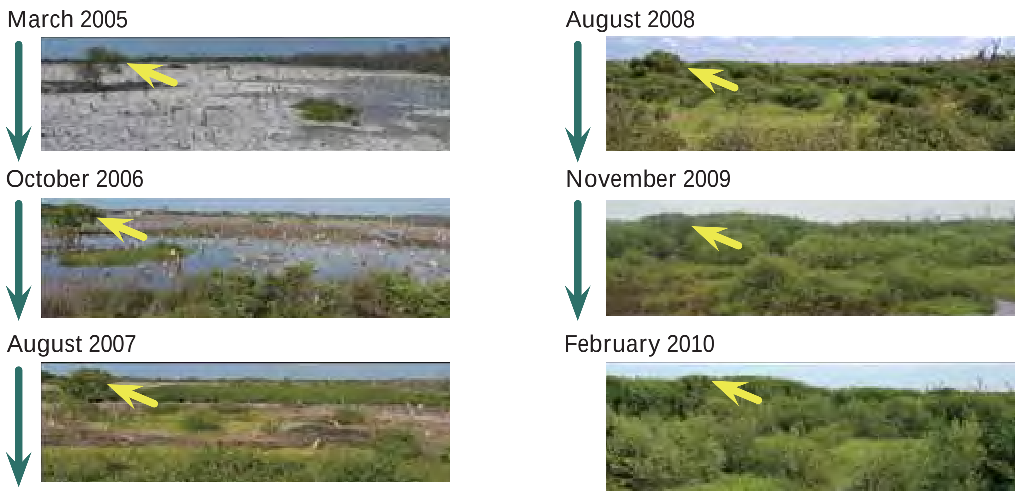

Figure 4.2 Chronological sequence of the restoration process of planted mangroves in Block A, Celestun

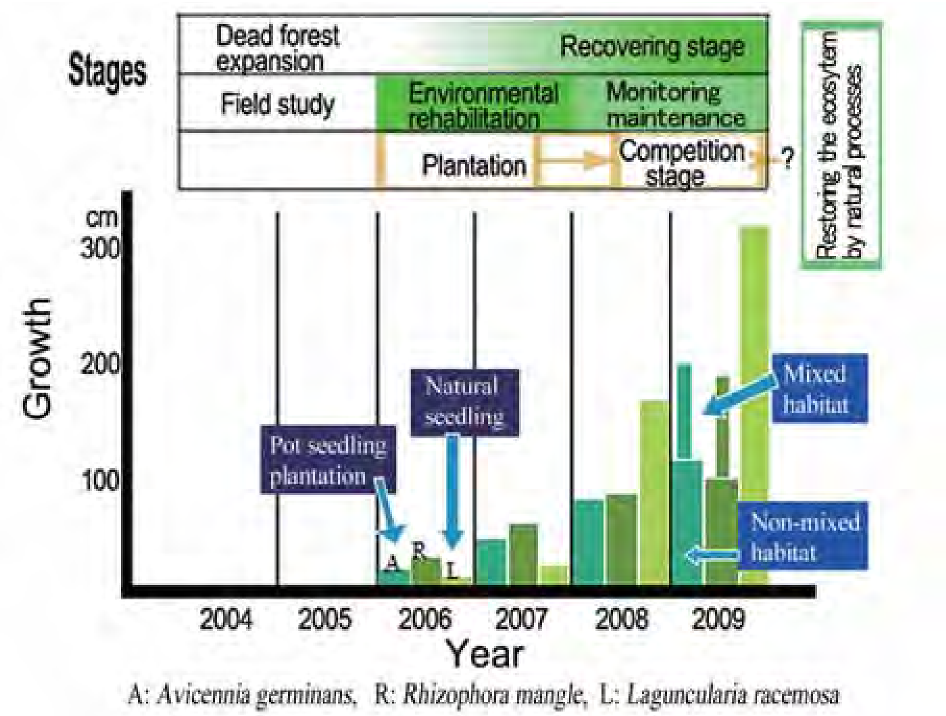

Figure 4.3 Mangrove plantation growth and development after restoring the tidal regime

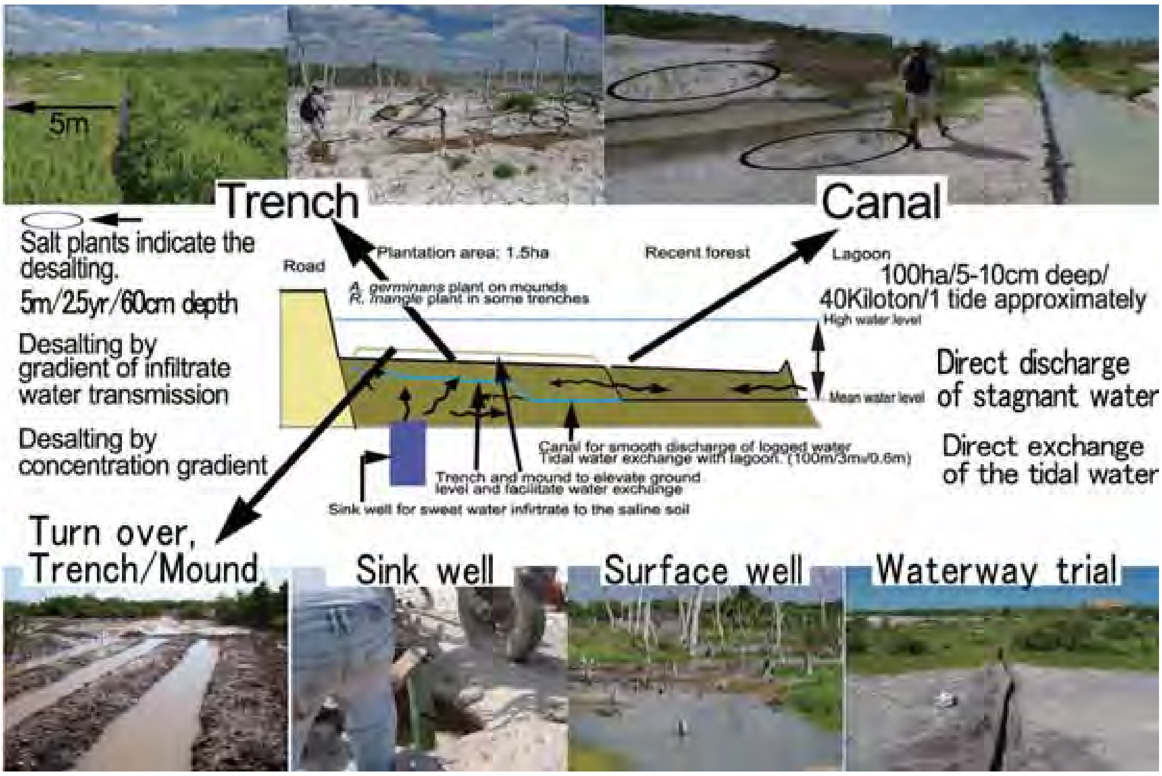

Figure 4.4 Different methods used for tidal flow recovery and their effects

Figure 4.5 Local people are employed to construct a canal (photo by K. Tsuruda)

Figure 4.6 Monitoring the salinity of the soil (left) and water (right) of the planting sites

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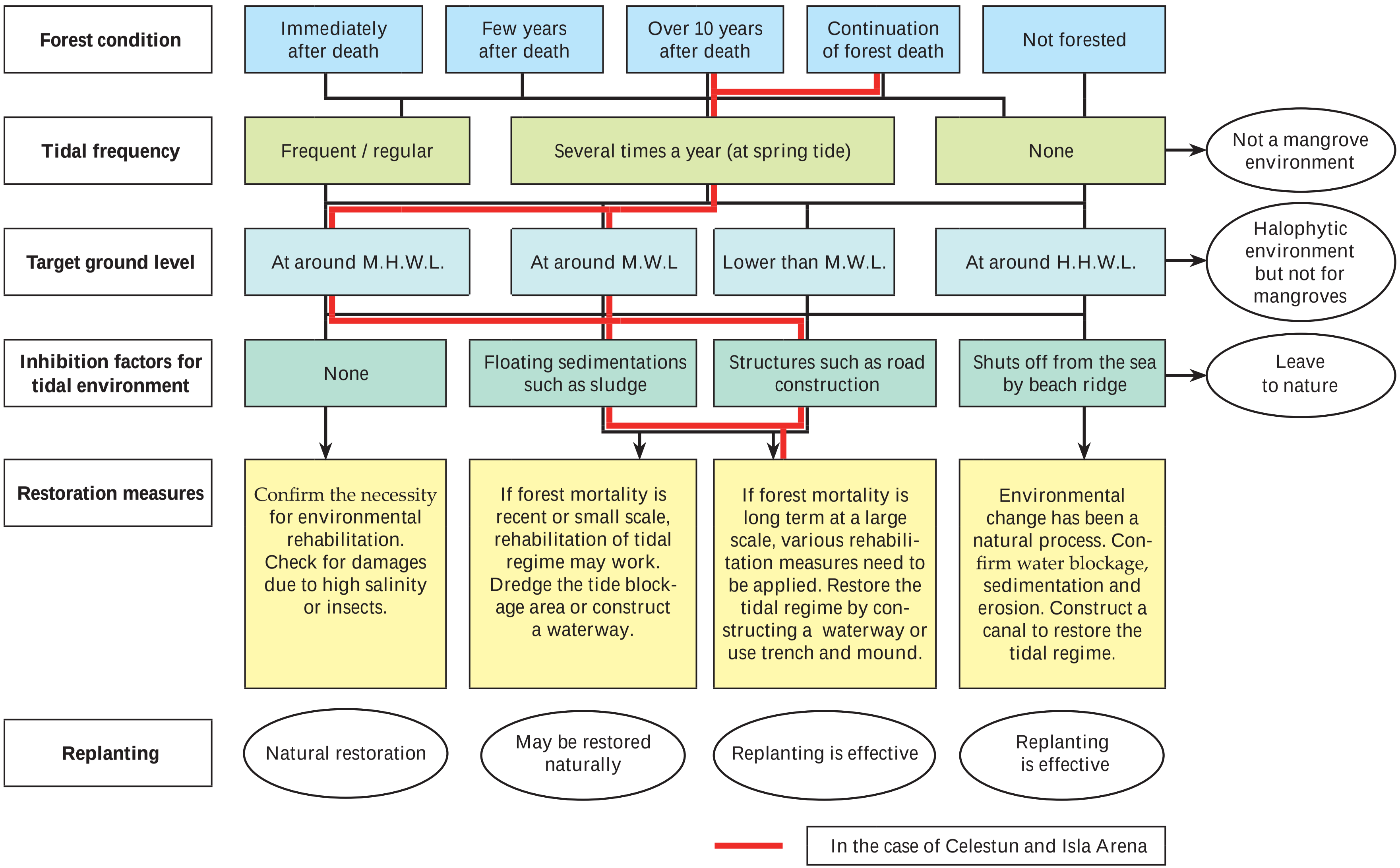
Appendix I Map of Yucatan Peninsula, Mexico

Appendix II Decision Making for Mangrove Restoration



Appendix III

Key Concepts for Mangrove Evaluation

Aerial photography: Aerial photograph taken with 25 x 25 cm negative file has recorded high resolution of the land coverage. This is an inexpensive way to obtain information on chronological change of the land. When analyzing aerial photographs, it is important to compare the photograph with ground survey (ground-truthing). Always bring along aerial photographs to the site and relate what you see from the photo to what you actually see at the site.

Canal (waterway): Canal construction is an effective, labour-saving and economical measure to restore tidal regimes. The success of canal construction for restoring tidal flow is to determine the height of ground level within the canal. There is no reason to dig a deep canal since mangroves only grow above mean water level. However, if there is one high ground level in the canal, then movement of the ebb and flow is determined at the level. Once the canal is constructed, it is important to check carefully the tidal flow throughout the whole waterway and improve where necessary to make sure there is no water stagnation.

Cenote: A deep natural pit or sink hole, characteristic of the Yucatan Peninsula, resulting from the collapse of limestone bedrock that exposes ground water underneath.

Chaparro mangroves: A fringe type of mangrove forest which establishes at the landward of lagoons. In Ria Celestun, generally soils in such lowland is high in salt content and dwarf *Rhizophora mangle* forests are formed.

Chenier: A sandy beach ridge that is part of a strand or chenier plain consisting of cheniers separated by intervening mud flat deposits with marsh and swamp vegetation.

Coppicing: A vegetative form of reproduction in plants where new individuals arise from stumps, roots or fallen trees. In chaparro mangroves, new stem growth is observed coppicing from stilt roots of *Rhizophora mangle*. This feature was not observed in *Avicennia germinans* or *Laguncularia racemosa*.

Diameter at breast height: Diameter of tree boles measured at breast height of 1.4 m (dbh) above the ground using a diameter tape.

Dioecious: Unisexual plant species with male and female flowers in separate individuals.

Fauna indicators: Among the various fauna in mangrove forest, crustacean such as crabs are sensitive to water environment. However, there is hardly any data indicating which type of crab tolerates what level of water. It will be necessary to collect such data.

Flowering and fruiting characteristics: Mangroves flower and fruit throughout the year with the peak season during the wet season. When forest gaps occur, the neighbouring *Rhizophora* trees tend to produce propagules more intensively.

Fringe type of mangroves: In Ria Celestun, this forest type establishes along the shoreline of coastal lagoons behind beach ridges.

Ground level: This is one of the importantly environmental factors for mangrove establishment. It directly relates to tidal flow and the depth of tidal inundation during the wet season, which are critical aspects for environmental restoration. Ground level also correlates to survival and growth rate of planted seedlings.

Infiltration well: This is an effective way to dilute soil salinity. In the Yucatan Peninsula, the well utilizes the gravity and pressure of confined freshwater aquifer at 5–10 m depth. Underwater current is generally very slow and it will take some time to see the effect. One effective way to facilitate the flow rate is to construct an open canal and release the pressure.

Inter-chenier mangroves: This mangrove forest type is formed behind beach ridges in low-lying depressions between layers of cheniers.

Mangrove floor deposits: When mangrove establishes, sand containing organic matter or peat including mangrove roots, accumulate on the forest floor. When mangrove dies, the sun reaches the forest floor and increases water temperature, resulting in sulphate acidification of surface soil and production of sludge by organic matter decomposition. Such sediments accelerate forest death.

Mangrove rehabilitation: Restoring the structure and functions of mangrove forests that have been degraded or depleted.

Mangrove restoration: Intentional restocking of degraded or depleted mangrove forests.

Necrosis: The death of cells or tissues.

Peat: In mangrove forests, peat consists of living and dead roots of *Rhizophora mangle* and *Avicennia germinans*, and fine organic matter broken down by crustaceans. In general, the organic content on the forest floor is high as salt delays decomposition, resulting in the accumulation of peat.

Petene: Mangrove forests of the petene type are specific to the Yucatan Peninsula, which are formed over a low and flat karst landscape. They are sometimes dome-shaped due to the discharge of freshwater spring at the intertidal zone.

pH: As with salinity measurement, it is recommended to take an undisturbed core soil layer to measure pH at a given depth. Seawater and the surface forest floor of the fringe type of mangroves are slightly alkaline. However, most mangrove deposits are slightly acidic. When mangrove trees die or are felled, the floor is exposed to sun and ferrous sulphide (FeS_2) in the deposit becomes sulphuric acid and ferric oxide (hematite) ($H_2O + 2FeS_2 \rightarrow H_2SO_4 + Fe_2O_3$). Acid sulphate soils are formed and this further deteriorates the environmental condition.

Plant stress: Factors that inhibit plant growth are called stress. Plants respond to stress by adaptation, defending or reaction, but high stress will cause to death. Stress level of mangroves can be determined in the field. For example, if the perimeter of *Rhizophora* leaves become wavy, phosphate is lacking. If the leaf colour is faint, nitrogen is lacking.

Pneumatophores: These are aerial roots, which develop from underground horizontal roots.

Propagules: In the mangroves, propagules develop from seeds that germinate while still attached to the parent tree. They germinate to produce new individuals.

Salinity measurement: Salt concentration can be easily measured from surface water using a salinometer. It is extremely difficult to measure soil salinity especially free water at the depth of roots. This is because the mangrove forest floor is generally saturated and if a hole is made water pressure would change and the soil water would move upright. It is recommended to use a gioslicer to sample an undisturbed core soil layer.

Salinity: Salt is generally toxic to plants, and the existence and health of mangroves are dependent on soil salinity. In Ria Celestun, there is a clear relationship between salt content in the soil and *Rhizophora mangle* forests. *Avicennia germinans* and *Laguncularia racemosa* have relatively higher and lower salt tolerance, respectively.

Satellite imageries: In recent years, it is becoming cheaper to obtain high resolution satellite imageries for analysis (remote sensing). Just as interpreting aerial photographs, it is strongly recommended to confirm the imageries with ground surveys.

Soil ploughing: To desalinize soils less than 30 cm depth, ploughing may be effective when the salinity of the surface water is lowest during wet season. The work is laborious when done manually with scoops. Mechanical ploughing is rapid and more effective.

Surface well: There is a confined freshwater aquifer at 5–10 m depth in the Yucatan Peninsula. A surface well can be used to pump up fresh water to reduce surface soil salinity.

Tidal elevation of mangroves: Mangroves grow at the upper level of the intertidal zone. Several topographical conditions satisfy these specific areas. Some beach ridges facing the open sea have such topography, however due to swash, trees cannot establish.

Tidal flat mangroves: This forest type establishes on the extensive tidal flats of lagoons.

Tidal level: Tide fluctuates time to time. Depending on the area, it can be diurnal, semi-diurnal and mixed. Mean water level (M.W.L.) is calculated by the sum of tidal height of all peaks in a year divided by the number of peaks. Mean high water level (M.H.W.L.) is calculated by the sum of tidal height of all high tides in a year divided by the number of high tides. In the same way, highest high water level (H.H.W.L.), mean low water level (M.L.W.L.) and lowest low water level (L.L.W.L.) can be calculated.

Trench and mound: This system of site treatment is sometimes used to facilitate the tidal water exchange at the planting site. Where soil salinity is high, it is especially efficient way to decrease the surface layer salinity by flushing.

Wave-like pattern mortality: A phenomenon where trees die in a patchy wave-like pattern. In the Yucatan Peninsula, this form of forest mortality was observed in tidal flat mangrove forests, adjacent to lagoons.

Silviculture Manual for Mangrove Restoration in the Yucatan Peninsula, Mexico

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Key words: Mangroves, restoration, planting trials, Yucatan Peninsula, Mexico

1. Introduction

This silviculture manual is prepared based on one-year results of the mangrove planting trial in Celestun and Isla Arena, Yucatan Peninsula, Mexico. The planting trial was part of the Mangrove Environment Rehabilitation Project of the Coastal Wetland Conservation Program of the Yucatan Peninsula, implemented from March 2003 to February 2008 by the Ministry of Environment, Mexico, and the Japan International Cooperation Agency (JICA).

It is expected that this silviculture manual will provide useful information for foresters and technicians who can play practical roles in the field, and also for resource managers and planners, and members of the general public who are interested in mangrove conservation and restoration.

Guidelines in this manual could be adapted for other areas in the west coast of Yucatan Peninsula depending on site conditions such as soil types, tidal regime, micro-topography, flowering and fruiting seasonality, etc. In no way complete or exhaustive, the manual can be amended and improved as new knowledge and experiences are gained through the application of the guidelines.

2. Preliminary Survey

For successful mangrove restoration, it is essential to carry out preliminary field investigations on the status of existing forests. Information to be gathered should include the extent of forests, causes of damage, socio-economic profiles, local needs and degree of environmental deterioration.

Following the preliminary investigations, selection of planting sites and choice of species become important key factors for the mangrove restoration. Site preparations, planting techniques and rehabilitation will inevitably be needed if natural regeneration is not expected.

However, we must take into account cost-effective considerations, in case engineering measures such as canal digging or soil ploughing are needed. Needless to say, it is better to achieve sustainable mangrove restoration by adopting low-cost technology as much as possible.

2.1 Selection of Project Areas

The selected project areas are in Celestun and Isla Arena (Figure 2.1) of the Ria Celestun National Biosphere Reserve, where cutting of trees for commercial or domestic use is prohibited. The objectives of the mangrove restoration are not intended for forestry operations but for coastal protection, ecosystem enrichment and aesthetic enhancement for the communities. Enabling the recovery of the mangroves to their original state would be the ultimate goal of the plantation trials.

Figure 2.1 Location of the project areas

Planting of mangroves was undertaken in three blocks at Celestun and in four plots at Isla Arena (Figure 2.2). The sites for test planting were selected carefully because site conditions varied considerably from place to place in terms of edaphic, topographic, hydrological, biological and social factors. Examples of the planting sites in Celestun and Isla Arena are shown in Figure 2.3. The planting sites in Celestun and Isla Arena, including their advantages, disadvantages, restoration feasibility and priority are described in Table 2.1 and Table 2.2, respectively.

When choosing the planting sites for mangrove restoration, remnant trees and regenerated seedlings are

Figure 2.2 Plantation blocks in Celestun (left) and plantation plots in Isla Arena (right)

Figure 2.3 Block A in Celestun (left) and inundated Plot 4 in Isla Arena (right)

good indicators of restoration possibility and success. These natural occurring trees and seedlings should therefore retained and managed with the best care.

Furthermore, locations where the ground level is low and water remains stagnant for prolonged periods are to be excluded from the plantation sites. Under water-logged conditions, the aerial root systems of mangroves especially *Avicennia germinans* might be suffocated.

2.2 Choice of Species

The mangrove species have their own habitat preferences according to the ground elevation, inundation frequency, soil salinity and other factors. So the selection of the appropriate species for planting is of utmost importance. Four mangrove species and one mangrove associate are found growing in Celestun and Isla Arena. They are:

- *Avicennia germinans* (black mangrove)
- *Rhizophora mangle* (red mangrove)
- *Laguncularia racemosa* (white mangrove)
- *Conocarpus erectus* (button mangrove)
- *Thespesia populnea* (mangrove associate)

Judging on the distribution and species composition of remnant forests and natural regeneration, and on site conditions such as high soil salinity and prolonged submergence, the project selected *Avicennia germinans* and *Rhizophora mangle* as promising species for restoration.

In general, *Avicennia germinans* is more adaptable and resistant to high soil salinity and its growth in early stages will be secured if the conditions are stable. Under soft muddy conditions that are frequently submerged, *Rhizophora mangle* is favoured due to its tolerance.

2.3 Site Preparation

Even if the appropriate species and suitable sites are selected, restoration in the deteriorated environment would remain difficult without employing measures

Table 2.1 Planting sites in Celestun: advantages, disadvantages, restoration feasibility and priority

Site	Advantage	Disadvantage	Restoration feasibility	Priority
Block A	• High accessibility • Demonstration effect • Environmental education • Remnant trees • Previous planting trials	• Frequently submerged • Seldom tidal flushing • Salt accumulation in soil • Clayey soil in part • Dumping ground • Scattered broken glass	Low	1
Block B	• Good accessibility • Organic soil	• Frequently submerged • Seldom tidal flushing • Salt accumulation in soil • Sparse vegetation • Sewage inflow	Low	3
Block C	• Good accessibility • Organic soil • Remnant trees • Close to pond/lagoon • Ecotourism potential	• Frequently submerged • Seldom tidal flushing • Salt accumulation in soil • Sparse vegetation • Invisible from main road	Low	2

Table 2.2 Planting sites in Isla Arena: advantages, disadvantages, restoration feasibility and priority

Site	Advantage	Disadvantage	Restoration feasibility	Priority
Plot 1	• High accessibility • Remnant trees • Recovery tendency • Natural regeneration	• Frequently submerged • Seldom tidal flushing • Salt accumulation in soil • Clayey soil in part	Medium	2
Plot 2	• Good accessibility	• Frequently submerged • Seldom tidal flushing • Salt accumulation in soil • Clayey soil in part • Relatively far from road • Sparse vegetation	Low	4
Plot 3	• Good accessibility • Organic soil in part	• Frequently submerged • Seldom tidal flushing • Salt accumulation in soil • Sparse vegetation	Low	3
Plot 4	• High accessibility • Remnant trees • Recovery tendency • Natural regeneration • Organic soil in part • Relatively low salinity	• Frequently submerged • Seldom tidal flushing • Salt accumulation in soil • Clayey soil in part	Medium to high	1

to alleviate or mitigate the current problems associated with hyper-saline soil conditions during the dry season and prolonged submergence during the rainy season. The project conducted several trials of site treatment. They included soil ploughing, trenching and mounding, canal digging, well digging and mulching (Table 2.3). Trenching and mounding, canal digging and well digging operations are illustrated in Figure 2.4.

It is too early at this stage to draw any conclusions based on results of the one-year trial. We need more observations and monitoring in order to evaluate the cost-effectiveness of the various trials of site treatment aimed at improving the harsh environments of the planting sites. It is crucial that tidal drainage is facilitated and that stagnant water is drained out to the lagoon or sea during low tide, and that the salt content is reduced in the surface soil.

Table 2.3 Site treatment trials conducted by the project

Site treatment	Trial site (date)	Operation	Effect and evaluation
Soil ploughing	Celestun (Apr 2006) Isla Arena (Jan 2006)	Hoed and ploughed the soil (30 cm deep)	• Salinity decreased in surface soil • Effective in early stages • Permanent effects unknown • Soils turned soft
Trenching and mounding	Celestun (Apr 2006) Isla Arena (Feb 2006)	Dug trenches (15 cm deep and soil heaped up as mounds on the sides)	• Salinity decreased in surface soil • Alleviated submergence • Effective in early stages • Permanent effects unknown • Retarded root development of *Avicennia germinans*
Canal digging	Celestun (Jun 2006)	Dug a canal (3 m wide, 60 cm deep, 600 m long connecting to the lagoon)	• Facilitated tidal drainage • Salinity decreased in surface soil • Effective for longer period • Natural regeneration on banks
Well digging	Celestun (Mar 2006)	Dug four wells in Block A. Three wells provided large amounts of water. Two wells were inter-connected	• Salinity decreased in surface soil • Permanent effects unknown • Problem of water stagnant and flooding
Mulching	Celestun (Jan 2007) Isla Arena (Feb 2006)	Used shading nets in Isla Arena and palm fronds in Celestun for mulching	• Effective in early stages and during dry seasons • Alleviated submergence • Permanent effect unknown • Too costly to use shading nets in the field

Figure 2.4 Digging a canal (left), trench and mound system (middle), and digging a well (right)

3. Nursery Techniques

The project has set up temporary nurseries both in Celestun and Isla Arena since late 2005. In Celestun, the nursery was previously established beside an abandoned pond near the lagoon. In spite of daily watering, seedlings showed poor growth and low survivorship when transplanted due to improper nursery management. A new nursery was established on the beach ridge of Block A which gets inundated during high tide. Its production capacity is 20,000 seedlings. In Isla Arena, the nursery is located at Remate, about 20 km far away from the village and 10 to 15 km from the planting sites. It produces up to 40,000 seedlings. The nurseries in Celestun and Isla Arena are shown in Figure 3.1.

Generally, it is not required to raise potted seedlings of *Rhizophora mangle* because the viviparous propagules can be planted directly in the field. However, the potted seedlings may be useful when transplanting is done during the non-fruiting season. Planting of nursery-raised seedlings is rather costly, time-consuming and laborious compared to direct planting of propagules. In a well-managed plan of restoration program, the quantity of potted seedlings to raise must be decided.

3.1 Nursery Site Selection

If possible, it is recommended that mangrove nurseries be established in upper intertidal zone so that manual irrigation is kept minimal. Some required conditions when selecting the nursery site are as follows:

- Upper intertidal zone with regular tidal flow
- No water-logging at low tide
- Surface soil salinity not exceeding that of seawater
- Sheltered from strong currents and waves
- Close vicinity to seed sources and planting sites
- Protected from intrusion by stray dogs and other animals
- Availability of soils for potting
- Availability of water resources for irrigation
- Easy access by car or boat
- Relatively firm ground for placement of potted seedlings

Figure 3.1 The previous nursery (top) and present one at Block A in Celestun (middle), and the Remate nursery in Isla Arena (bottom)

3.2 Collection of Seeds/Propagules

Collection can be done by either gathering freshly fallen seeds/propagules or plucking them directly from the mother trees. Care should be taken to ensure that they are fully matured, free from insect damage and have not started to root.

Seed/propagule maturity is judged by its weight, size and colour. When matured, the seed coat of *Avicennia germinans* changes from light green to yellowish green. Maturity in *Rhizophora mangle* propagules is recognized by their reddish or yellow collar.

Being crypto-viviparous or viviparous, seeds/propagules cannot be kept for long. Therefore, it is better to sow them as soon as possible on the same or following day of collection. If the seeds must be stored for a while, they should be kept under shade in brackish water for *Rhizophora mangle* and in carton box for *Avicennia germinans* seeds. Useful guidelines for collecting and handling seeds or propagules are summarized in Table 3.1.

3.3 Sowing and Nursing

Polyethylene bags or poly-bags measuring 8 cm in diameter and 12 cm in height are recommended as pots for seedlings. Holes (8 to 10) are punched onto the side and bottom of each bag for soil ventilation and permeation. Bigger bags are more cumbersome when transporting and transplanting seedlings.

As soil potting is time-consuming work, the preparation should be started before the fruiting season. Beach sand is better as pot soils, but salt-accumulated sand must be avoided. The use of fertilizer is not necessary. However, it is worthwhile to conduct a simple experiment using slow-release fertilizer of the NPK type.

Sowing the seeds in pot soils is to be done during neap tide. The depth of sowing is one third of seed/propagule height. If seeds of *Avicennia germinans* are completely buried into the soil, the germination rate is very low.

Most mangrove species are light demanding. However, for securing the higher germination rate and better early growth, some shading may be required. Plastic shading nets or palm fronds can be used. Shading can be removed one month before transplanting in order to acclimatize or harden the seedlings. Artificial watering is needed once a day when natural irrigation during high tide is not possible. If stagnant water is formed at low tide, site draining is essential.

The recommended specifications for transplanting of seedlings are 10–20 cm in height, 6–8 leaves, 3 to 6 months after sowing for *Avicennia germinans*, and 20–30 cm in height, 4–6 leaves, 3 to 6 months after sowing for *Rhizophora mangle*.

Pests such as caterpillars and other insect larvae can cause damage to the seedlings by defoliation (Figure 3.2). If detected, it is necessary to discard them. If the damage is severe, the use of organic insecticides such as *Azadirachta indica* (neem) might be an option. Some guidelines for sowing, transplanting and nursing *Avicennia germinans* and *Rhizophora mangle* are described in Table 3.2.

Table 3.1 Guidelines for collecting and handling seeds/propagules

	Avicennia germinans	*Rhizophora mangle*
Propagule type	Crypto-viviparous	Viviparous
Fruiting season	August–October	July–September
Sign of maturity	Yellowish green seed coat	Yellow to reddish collar
Selection criteria	At least 2 g in weight	At least 20 cm in length
Pre-treatment	Peel off seed coats	None
Storage duration	Up to a week in carton box under shade	Up to two weeks in brackish water under shade

Table 3.2 Summary of sowing, transplanting and nursing

	Avicennia germinans	*Rhizophora mangle*
Pot soil	Beach sand preferable	Beach sand preferable
Fertilizer	Slow-release NPK type	Not necessary
Sowing	Bury 1/3 of seed	Insert 1/3 of propagule
Shading	0–25% shade	25–50% shade
Watering	Once a day at neap tide	Once a day at neap tide
Pest control	By hand preferable	By hand preferable
Transplanting	10–20 cm, 6–8 leaves	20-30 cm, 4–6 leaves

Figure 3.2 Ground-dwelling larvae of Coleoptera and a caterpillar of Lepidoptera feeding on leaves of *Avicennia germinans*

4. Planting Procedures

4.1 Preparatory Work

A well-managed planting program requires sound planning in advance, depending on factors such as quantity and quality of available seeds/seedlings, tidal conditions and workforce. Prior to the actual planting operations, garbage in the sites should be collected and discarded. Broken glass fragments scattered or buried in Block A of Celestun are dangerous for the workers and should be excluded from the planting sites. Sewage and other wastes in Block B of Celestun require appropriate remedial measures.

4.2 Transporting Planting Materials

During transportation of planting materials such as seeds, propagules and potted seedlings to the planting sites in the field, care must be taken so that they are not damaged. Usually, planting materials are transported by truck, trailer or boat for the long distances (Figure 4.1), and by bucket, basket, baby bath-tub or wheelbarrow for the short distances. It is essential that only sufficient quantities of seeds, propagules and seedlings are transported to the sites for planting on the same or next day to avoid storage in the field.

4.3 Planting Operations

It is advisable that the planting sites be located on higher ground to avoid prolonged submergence. Planting in blocks or islands (Figure 4.2) and strip planting on mounds (Figure 4.3) can be a good choice.

The period for planting is dependent on the fruiting season and the availability of potted seedlings. It is better to avoid the driest months when soil salinity is extremely high. Nursery seedlings should be transplanted in the planting sites within 6 months or 12 months at the latest. The best planting seasons for both species are as follows:

Avicennia germinans:

- August to October for direct planting in Celestun, and Isla Arena
- January to March for seedling transplanting in Celestun, and February to March or July in Isla Arena, when the water level is low enough

Rhizophora mangle:

- July to September for direct planting in Celestun and Isla Arena
- January to March for seedling transplanting in Celestun and February to March in Isla Arena, when the water level and salinity is low

Figure 4.1 Transporting mangrove seedlings by trailer (left) and canoe (right)

Figure 4.2 Block or island planting of *Avicennia germinans* (left) and *Rhizophora mangle* (right)

Figure 4.3 Strip planting of *Rhizophora mangle* and *Avicennia germinans* on mounds

In Isla Arena, a batch of *Rhizophora mangle* seedlings transplanted in April had withered due to prolonged submergence (Figure 4.4).

Figure 4.4 Withered seedlings of *Rhizophora mangle* transplanted in April in Isla Arena

As for direct sowing of *Avicennia germinans* seeds in the field, group or cluster planting of 3–4 seeds is recommended. As tidal flow and current may wash away the planted seeds, direct sowing should be carried out during neap tide. This method of planting applies only to Celestun, but not to Isla Arena where the water level is too high.

So far, the project has not reached any conclusion concerning the optimum planting densities. Too close spacing between the seedlings might be stressful to the plants, and lead to poor survival and growth. Considering that the purpose of restoration in Yucatan is not for forestry production but recovery of devastated ecosystems, the planting density could be 1 x 1 m or 1 x 0.5 m.

Planting holes for the potted seedlings should not be shallower than the pot height. Where the soil is soft enough, holes can be dug by hand. In more compacted soil, holes can be made using a hoe or shovel.

At the time of transplanting, the poly-bags should be carefully removed so as not to break the ball of soil around the roots or not to cut the roots extending out of poly-bags. It is important to collect all used poly-bags afterwards, and not to leave anything in the field.

Finally, safety should come first all the time at every place. Workers are advised to use proper footgear and clothing. They are alerted to the offensive hazards in the field such as broken glasses, in order not to be injured. The field manager of the project must ensure the safety and good health of the workers.

5. Tending and Monitoring

After the planting operation, tending and monitoring the survival and growth of mangroves in the planting sites are strongly recommended. The objectives of such operations are also to identify adverse factors and to implement counter-measures. Their frequency can be on a weekly basis for the first month and monthly afterwards.

5.1 Adverse Factors and Counter-Measures

Adverse factors which affect the survival and growth of mangroves can be physical or biological in nature, and proposed counter-measures are intended to mitigate these adverse effects. Possible causes of impediments and counter-measures are shown in Table 5.1.

Among the causes which impede the survival and growth of planted seedlings, high salt content in the soil and prolonged submergence in low-lying habitats are the most problematic and chronic in the planting sites. Site desalination and drainage are difficult tasks incurring much cost. In most cases, the other causes of damage are minor, temporary and limited in extent, so the special attention might not be needed.

5.2 Supplementary Planting

Should most of the seedlings transplanted withered within a very short period, we must consider the following questions:

- Were the species selected appropriate for the planting sites? (*Avicennia germinans* prefers the higher ground levels)
- Was the season and timing of the planting appropriate? (It is better to plant the seedlings during low tide)
- Were conditions of seedlings transplanted good and sound enough? (Healthy and well-grown seedlings should be planted in a careful manner)
- Were causes of poor results identified? Were they catastrophic or not? (Usually, the causes are not simple but involve a combination of factors)
- Were proper planting methods applied? (If direct planting fails, try potted seedlings)

After identifying and resolving the problems and adverse factors causing damage to planted seedlings, counter-measures should be carried out before considering the need for supplementary planting.

The project has not yet reached an agreement upon the existing number of residual trees per unit of rehabilitated area. The purpose of restoration in the Yucatan Peninsula is not for commercial or domestic wood production, so the density control could be left to nature. Probably 1,000 trees/ha should be more than enough several years after the planting. It is proposed that supplementary planting be implemented only when the mortality rate exceeds 50% within one to two years of planting. Counter-measures taken are expected to be successful.

5.3 Evaluation of Restoration

It is very difficult at this stage to evaluate the success or failure of the restoration project in Celestun and Isla Arena. Transplanted seedlings have suffered from

Table 5.1 Causes of impediments, symptoms and counter-measures

Cause of impediment	Symptom of mangrove damage	Proposed counter-measure
High salinity in the soil or surface water	Acute physiological malfunction, leading to dieback or withering	Site desalination by digging canal
Prolonged submergence	Suffocate roots, leading to dieback or withering	Avoid planting in lower elevations Construct drainage canals and plant *Rhizophora mangle* on mounds
Strong winds by storms or hurricanes	Blown down or defoliate	None
Strong currents or flows	Uprooted and washed away	Exclude from the planting area
Clayey deoxidized soil (reduction)	Suffocate underground roots, leading to withering	Exclude from the planting area
Trash or floating objects	Adhere to plants and stifle growth	Remove by hand or set up protective nets
Caterpillars and other insect defoliators	Leaves eaten	Remove by hand or apply organic insecticide
Stray dogs	Trampling of plants	Enclose the planting site with temporary fences

various damages in some sites but partly survived with slow but steady growth in other sites. At least a couple of more years shall be taken to evaluate the rehabilitation trials conducted by the project.

Figure 5.1 shows the planting activities implemented in Celestun from 2006 to 2007. The green oval border-lines indicate good results so far. Better growth of transplanted *Avicennia germinans* seedlings is found in the following places:

- On the beach ridge in Block A (Figure 5.2)
- Beside the main canal
- On the artificial mounds with neighboring trenches in Blocks B and C
- At slightly higher ground levels

In lower elevations of Isla Arena, where water is stagnant persistently, seedlings withered within 2–4 weeks after the transplanting. In Celestun, even where sufficient water is available and soil salinity is low enough in the vicinity of the man-made wells, survival was extremely low.

The survival rate of *Avicennia germinans* transplanted on the beach ridge of Block A in March 2006 was 60% as of February 2007. The average height was 35 cm and mean number of leaves was 65. Under better conditions on the mounds, the plants reached 60 cm in height with up to 300 leaves.

In Block C, where the direct planting of *Avicennia germinans* and *Rhizophora mangle* was conducted from September to October 2006, almost all propagules germinated without any problem and showed high survival and growth performance during the first six months.

In Isla Arena, transplanted seedlings showed slow but steady growth with the exception of Plot 2 where survival rate was only 10–30%. In Plot 4, where the results were the most satisfactory, the data indicated that growth in early stages can be secured irrespective of any land treatment if the site conditions are favorable enough for the seedlings.

It is necessary to assess the physiological tolerance of mangrove species to prolonged submergence. In Isla Arena, the water is stagnant for almost half a year (August to February). Seedlings transplanted in July and September 2006 survived, however, growth was very slow. Studies on the micro-topography, tidal regime, degree of reduction in the sediment and water, surface water characteristics, and other possible limiting factors have to be carried out to clarify the differences in the results between Celestun and Isla Arena. Anyway, regular observations and monitoring are required over the next few years to evaluate the rehabilitation trials.

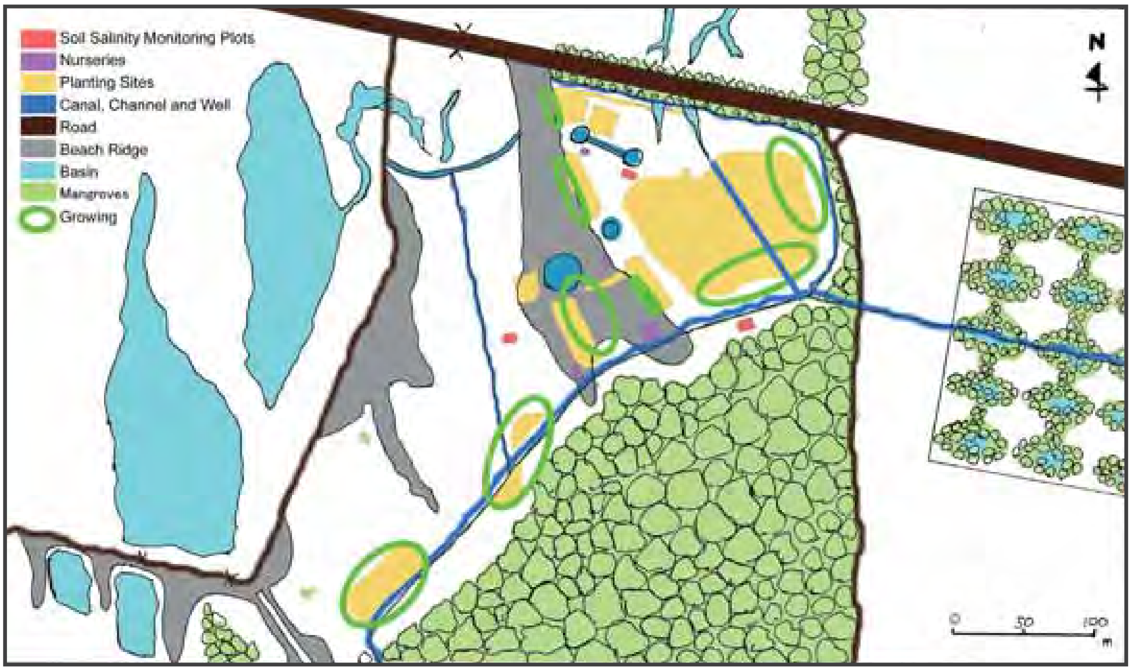


Figure 5.1 Implemented activities in Celestun from 2006 to 2007

Figure 5.2 Steadily growing *Avicennia germinans* on the beach ridge of Block A, Celestun

6. Conclusion

The following measures are recommended:

For Celestun, direct planting of *Avicennia germinans* and *Rhizophora mangle* are to be tried especially in Blocks B and C after making several trenches and mounds. The interval of trenches connecting to the principal canal can be made wider (possibly 5–10 m) than the current 1 m.

- The draining channel shall be established in Block A, and *Rhizophora mangle* propagules are to be planted in lower ground levels on a first-priority basis.
- The restoration efforts should be re-started from beside the principal canal, and then gradually extending inland.
- The construction of a small tidal nursery with production not exceeding 10,000 seedlings and managed by a permanent employed worker is recommended.

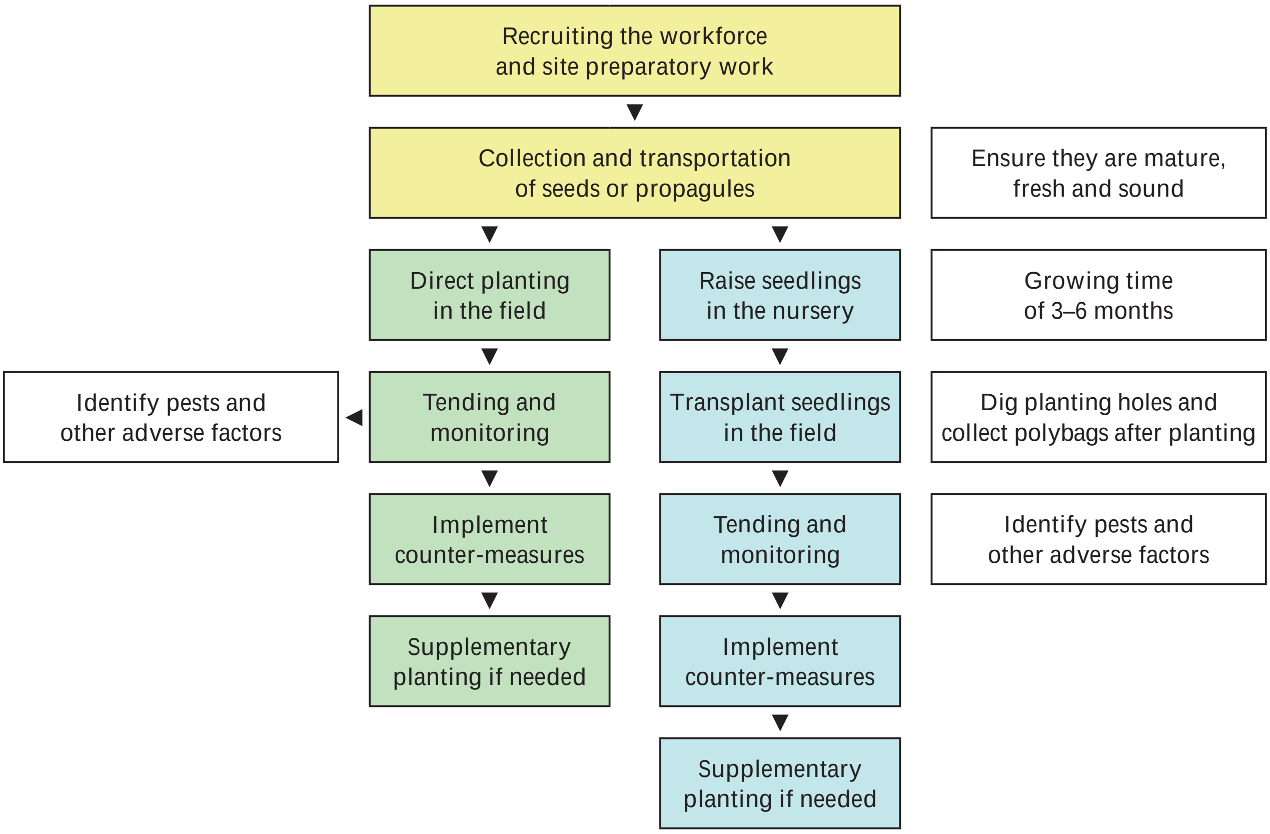
For Isla Arena, the possibility of constructing a drainage canal should be explored. With the canal, site treatments such as ploughing, trenching and mounding may not be necessary. When planning and implementing the work, special attention is required not to damage the remaining trees.

- Restoration should start from Plot 4, and then expanding to surrounding locations.
- To some extent, the rehabilitation process can rely on natural regeneration.
- Direct planting of *Rhizophora mangle* should be adopted because the direct sowing of *Avicennia germinans* cannot be applied. Potted seedlings can be transplanted from February to March.

In general, a mid-term or long-term action plan is to be developed by the local authorities. The plan should include a flow chart of silviculture operations (Appendix I) and an annual calendar for mangrove planting (Appendix II).

In conclusion, this silviculture manual is preliminary, and can be amended and improved as new knowledge is gained. We hope that the local authorities will continue to execute the mangrove restoration trials in a sustainable and cost-effective manner on a trial-and-error basis not only for Yucatan but also for the global environment.

Appendix I Flow Chart of Mangrove Silviculture Operations



Appendix II Annual Calendar for Mangrove Planting

Species	Silvicultural activity	J	F	M	A	M	J	J	A	S	O	N	D
Avicennia germinans	Selecting planting sites												
	Preparation of the nursery												
	Collection of seeds & direct sowing												
	Raising seedlings in the nursery												
	Preparation of planting sites												
	Transplanting of nursery seedlings												
	Tending & monitoring of plantations												
Rhizophora mangle	Selecting planting sites												
	Preparation of the nursery												
	Collection of propagules and planting												
	Raising seedlings in the nursery												
	Preparation of planting sites												
	Transplanting of nursery seedlings												
	Tending & monitoring of plantations												

Activities of ISME

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