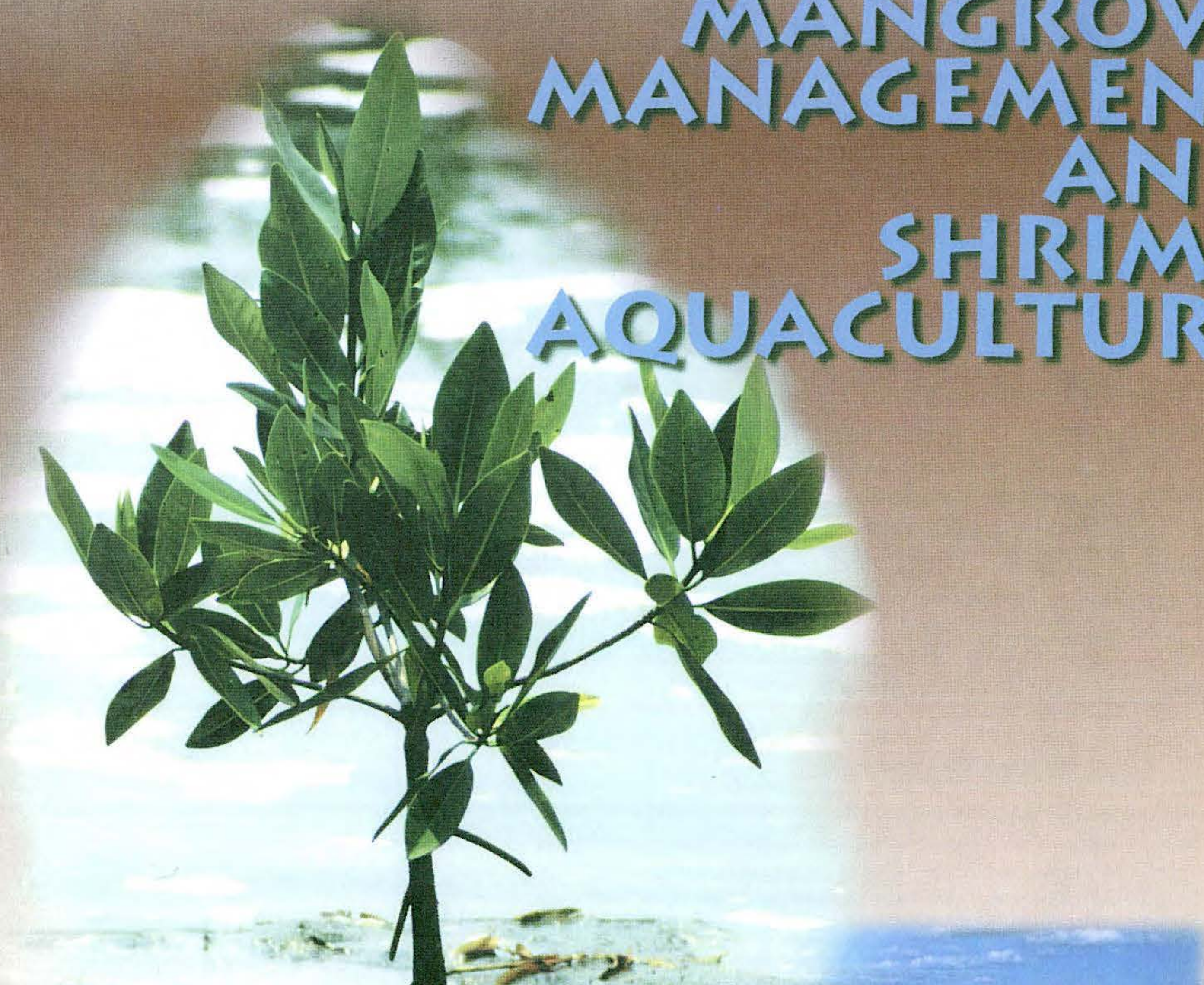
MANGROVE MANAGEMENT AND SHRIMP AQUACULTURE



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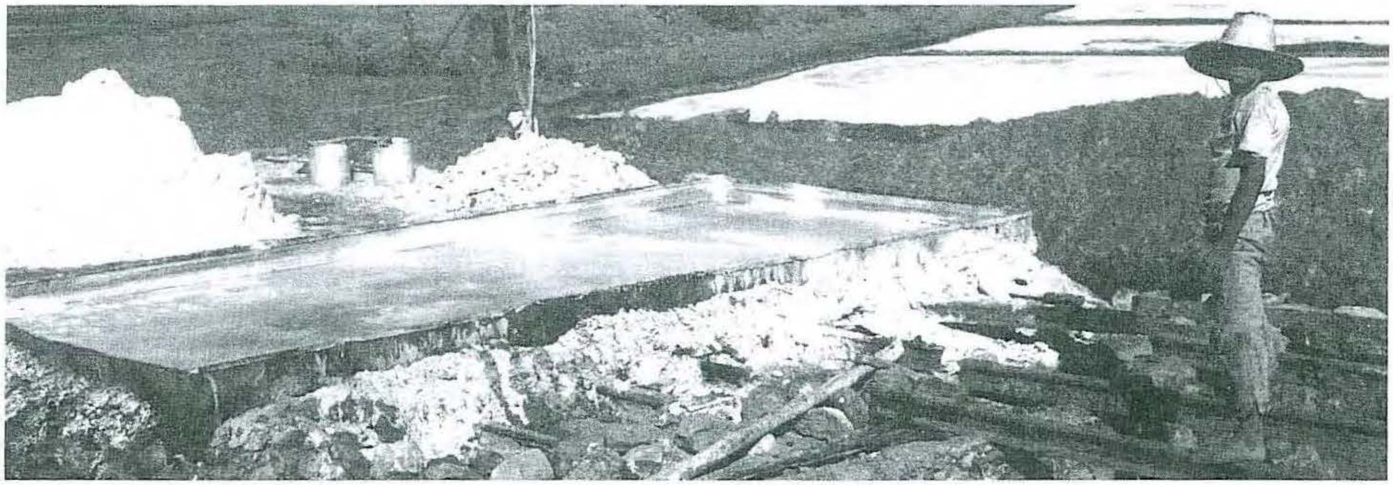


MANGROVE MANAGEMENT AND SHRIMP AQUACULTURE

LAURENCE MASSAUT

INTRODUCTION

OBJECTIVES

SHRIMP FARMING WORLDWIDE is accused of threatening mangrove forests, and in some regions, it is said to be a major cause of their destruction. Recent efforts by the aquaculture industry and some governments have concentrated on identification of strategies that can be used to minimize or eliminate damage to mangroves. In the general context of increasing interest in ecosystem conservation and sustainable exploitation, specific management procedures that will mitigate potential impacts of shrimp aquaculture on mangrove forests are needed.

Shrimp can be farmed in an environmentally safe and sustainable manner. In countries where practiced, the shrimp farming industry is providing many jobs and contributes greatly to economic development. On the other hand, mangroves are important because of their invaluable resources and services, and their protection is highly desirable. Mangrove wetlands are also important for shrimp farmers. They are the natural environment where post-larvae and juvenile shrimp dwell, they protect the coastal environment from storms, and they serve as biofilters to improve quality of coastal waters.

Recent literature on techniques for mangrove reforestation and management that could be applied by aquaculturists to help them minimize impacts on mangrove forests are reviewed. The objectives of this publication are the following:

1. To give general background information on mangrove ecosystems.
2. To summarize the interactions between shrimp aquaculture and mangrove forests.
3. To present a review on mangrove reforestation and management techniques.

SHRIMP AQUACULTURE AND THE ENVIRONMENT

In the last decade, concerns regarding the rapid development of the aquaculture industry, and especially of coastal shrimp farming, have appeared (Bailey 1988; FAO 1991; Primavera 1991; Phillips et al. 1993; Pullin 1993; Primavera 1995; Boyd 1997; Dierberg and Kiattisimkul 1996). Concerned groups have pointed out damage caused to the environment and have raised questions on the sustainability of aquaculture projects. They now recognize that environmental damage and social misconduct have occurred because of shrimp farming projects in some areas. However, such impacts were more common in the early days of aquaculture.

Technical knowledge for aquaculture is well established, and shrimp can be produced in a sustainable and responsible manner (Boyd and Massaut 1997; Clay 1997). In fact, the recent adoption of better site selection, pond construction, and production techniques has significantly reduced the occurrence of environmental impacts associated previously with aquaculture development.

Although this is not the focus of the present document, a short list of the major environmental concerns often associated with coastal aquaculture follows (Boyd et al. 1998):

- Conversion of mangrove forests and other wetlands to aquaculture farms.
- Eutrophication of natural waters by effluents from aquaculture operations.
- Increased sedimentation in natural water bodies as a result of pond effluents and disposal of pond sediment.
- Salinization of freshwater by pond effluents and seepage into aquifers.
- Negative effects on native fisheries and biodiversity through habitat destruction, water pollution, impingement by pumps, use of wild-caught broodstock and post-larvae, large by-catch when collecting wild post-larvae, and introduction of non-native species.
- Use of potentially toxic and bioaccumulative chemicals.
- Conversion of crop and pasture land to aquaculture farms.
- Excessive use of resources such as freshwater, feed ingredients, electricity, etc.
- Social misconduct.

Impacts of shrimp farming on mangroves are more than just cutting trees and clearing land. Sometimes the construction of a farm can result in water logging and hydrological changes that can impair mangroves at some distance from the farming site. For example, farm construction may cause salinity changes and stress mangrove trees not adapted to these new salinity levels. There are also concerns about diseases spreading from farmed shrimp into wild shrimp population.

Problems listed above should be addressed by both governments and the shrimp industry. Negative environmental impacts of shrimp farming can be alleviated through good site selection, use of adequate design and construction methods, operations according to best management practices, and consideration for the environment. Although there have been problems with sustainability of shrimp farming in some locations, other shrimp farm operations have been sustainable and profitable. Techniques for reducing adverse environmental impacts and enhancing sustainability need to be applied to the shrimp industry worldwide.

RATIONALE FOR CONSERVATION OF MANGROVE FORESTS

In the early 1970s as commercial shrimp farming began, mangroves were generally considered as waste lands with little intrinsic value, so their destruction was not discouraged by governments and planners (Mitsch and Gosselink 1993). This attitude did little to ensure productive and sustainable use of mangrove ecosystems and was responsible for major loss in mangrove forests during this time. However, today mangroves are recognized as economically and ecologically important, and common sense dictates that their use should be managed carefully. The ecological and social importance of mangrove ecosystems is clearly recognized and there is an urgent need for international cooperation, integrated management, conservation, and the collection and exchange of scientific data useful for their management. However, there is little agreement on the solutions and debate is fierce among scientists, economists, social planners, politicians, conservationists, and developers as to the actions that need to be taken.

Tropical mangrove forests are vital for their wealth of genetic diversity, nursery functions for aquatic species, protection of the coasts from storm surges, conservation, and environmental values. Large human populations in coastal areas of tropical countries are dependent upon the mangroves for firewood, construction materials, food, and medicinal resources. Mangrove exploitation can be sustainable if based on sound management procedures (Mitsch and Gosselink 1993). Mangrove forests can generate social and economic benefits to many tropical countries and serve important purposes for shrimp farming, thereby reinforcing the interest in their maintenance for all concerned. The difficulty is how to convince governments, developers, shrimp farmers, and local inhabitants that mangroves are a valuable resource and to persuade them to adopt best practices when deciding land utilization practices. There is an urgent need for wise utilization and sustainable management of mangrove resources.

A growing number of aquaculturists realize that better management practices need to be adopted. Aquaculture associations worldwide are trying to develop environmental guidelines for the industry. The purpose of such codes is to promote greater environmental awareness within the shrimp farming industry and to protect mangrove forests from adverse impacts of coastal aquaculture. Some of the management practices recommended may call for reforestation of abandoned ponds or any area that can sustain mangrove without adversely affecting the efficient operation of the shrimp farm. Such efforts should be encouraged and their development promoted, not just among aquaculturists and conservationists, but also within the larger community.

Mangrove Systems

Introduction

THE MANGROVE FOREST is an association of halophytic trees, shrubs, and other plants (including ferns and palms) growing in brackish to saline tidal waters on mudflats, riverbanks, and coastlines in the tropical and subtropical regions (Mitsch and Gosselink 1993). This vegetation is found in the zone inundated by the highest tides and exposed by the lowest tides. It exhibits physical and physiological adaptations to its unique environment. The word *mangrove* refers to both the dominant trees and to the entire plant community. Terms for these communities include mangrove, mangrove forest, coastal woodland, intertidal forest, tidal forest, mangrove swamp, mangrove wetland, and mangal (Mitsch and Gosselink 1993).

The species of plants known as mangroves belong to a wide variety of plant families with a common characteristic of tolerance to salt and brackish waters. Around seventy species of mangrove plants are recognized around the world, with the highest concentrations of species being encountered in Southeast Asia and Australia (Spalding et al. 1997). A complete list of mangrove species is found in Appendix 1. The largest mangrove forests are in Indonesia, Brazil, and the Sundarbans of India and Bangladesh. Within these forests live a host of animals, some of them derived from the land, but most coming from the sea (MacNae 1968).

Mangrove swamps are found along tropical and subtropical, sheltered coastlines throughout the world, usually between 30°N and 30°S latitude. Within these limits they are widely distributed, although natural mangrove communities are absent from many Pacific islands (Spalding et al. 1997). Table 2.1 presents estimates of total mangrove area in the world and compares regional totals from different references (Spalding et al. 1997).

TABLE 2.1: ESTIMATES OF MANGROVE AREAS (IN KM^2), TOGETHER WITH PERCENTAGES OF GLOBAL TOTALS (FROM SPALDING ET AL. 1997).

Region	Mangrove area IUCN 1983	Mangrove area Fisher and Spalding 1993	Mangrove area Spalding et al. 1997
South and Southeast Asia	51,766 (30.7%)	76,226 (38.3%)	75,173 (41.5%)
Australasia	16,980 (10.0%)	15,145 (7.6%)	18,789 (10.4%)
The Americas	67,446 (40.0%)	51,286 (25.8%)	49,096 (27.1%)
West Africa	27,110 (16.0%)	49,500 (24.9%)	27,995 (15.5%)
East Africa and the Middle East	5,508 (3.3%)	6,661 (3.4%)	10,024 (5.5%)
Total Area	168,810	198,818	181,077

The latest estimate of total area of mangrove forests in the world is around 181,000 km^2 (Table 2.1). This figure is thought to be a reasonable assessment, but there are likely to be considerable margins of error (Spalding et al. 1997). Because of difficulties in mangrove identification from satellite photographs and differences in definition, age, scale, and accuracy of different national sources, the use of global composite statistics as a baseline for monitoring changes in mangrove area should be employed with extreme caution. However, the area that mangroves occupy is of great interest in quantifying their presence and changing status. There is an urgent need in most places for more accurate mapping of mangrove areas at much higher levels of resolution.

Review by Regions

There are two main centers of diversity for mangrove communities which have been termed the western and eastern groups (Mitsch and Gosselink 1993). The eastern group broadly corresponds with the Indo-Pacific and is bound to the east by the limits to natural mangrove occurrence in the west and central Pacific, and to the west by the southern tip of Africa. The western group fringes the African and American coasts of the Atlantic Ocean, the Caribbean Sea and the Gulf of Mexico, and the western (Pacific) coast of the Americas. These two regions have quite different floristic inventories, and the eastern region has approximately five times the number of species that are found in the western region (Appendix 1; Spalding et al. 1997).

Total mangrove area is predominated by four countries: Indonesia (42,550 km^2), Australia (11,500 km^2), Brazil (13,400 km^2), and Nigeria (10,515 km^2). In total, these four countries represent 43% of the world mangroves and each accounts for 25-60% of the mangroves in their respective region (Spalding et al. 1997). Management decisions relating to mangroves in each of these countries will have a significant effect on the global status of mangrove ecosystems in the future.

South and Southeast Asia have a total mangrove area of 75,173 km^2 and represent 42% of the world mangrove forests (Table 2.1). Very long coastlines, large number of islands, and good shelter favor the development of mangrove in this region. However, tropical cyclones are common in the region and present a threat to mangrove development along some coastlines. Many authors consider the Indo-Malayan region to be the major center of origin for mangrove taxa, and that dispersal from here to other areas occurred particularly during the Tertiary and Quaternary geological periods (MacNae 1968; Spalding et al. 1997). Traditional exploitation of mangrove forests can be traced back many centuries and includes widespread use as lumber, thatching materials, fuelwood, charcoal, leather tanning, fodder, medicine, capture fisheries, and brackishwater ponds for aquaculture. Increasing population and economic growth have led to high pressure on mangroves and an increase in their exploitation. Extensive mangrove areas have been lost as a result of these pressures. However, there is a growing awareness of the importance of mangroves in Southeast Asia, and since the 1970s, mangrove committees have been established within government departments in many countries. Sustainable forestry practices are being encouraged and appear to be working successfully in a number of sites (Spalding et al. 1997). Bangladesh and Vietnam have undertaken large mangrove reforestation programs for at least 15 years with similar, though smaller, operations occurring in other countries (Field 1996).

The Australasian region includes Australia, Papua New Guinea, New Zealand, and the islands of the South Pacific (Spalding et al. 1997). The total area of mangroves in this region is 18,789 km^2 which represents 10% of the global mangrove area (Table 2.1). Australia dominates the region in mangrove coverage. Direct use of mangroves in Australia has never been important and vast areas of mangrove forests remain in pristine state. However, in some regions of Australia, mangrove forests have been cleared for urban development, ports, airports, and tourist resorts. In the South Pacific, mangroves are traditional grounds for fishing and collecting crabs and have been exploited for firewood and timber for construction of houses and boats. Recently mangrove forests have been cleared for coastal development.

Mangrove forests in the Americas stretch from Mexico, the southern United States and Bermuda in the north to Peru and Brazil in the south. The total area of mangroves in this region is 49,096 km^2 which represents 27% of the global mangrove area (Table 2.1). Hurricanes are a major natural phenomenon affecting mangrove systems, particularly in the Caribbean, and their frequency will dictate mangrove growth and development. Traditional uses of mangrove forests in the region are traced back many centuries and include timber harvesting, fishing in surrounding waters, oyster harvesting, and use as resins, fibers, tannins, dyes, and medicine (Spalding et al. 1997). Recently, large areas of mangroves have been cleared for the development of land for agriculture, grazing, urban development, shrimp farming, and the booming tourist industry, as well as for timber and fuel. Mangrove losses have also occurred when used for solid waste disposal, landfill for urban development, and from pollution brought by agricultural runoff and the oil industry. There is now a wide range of legislation in place throughout the region to conserve mangroves, including protection of mangrove areas, coastal zone management planning and restriction of land clearance, waste disposal, and timber cutting (Spalding et al. 1997). However, unlike Southeast Asia, few areas have been replanted with mangroves and there has been little silvicultural effort (Field 1996).

In West Africa, mangroves are found in all countries from Mauritania in the north to Angola in the south (Spalding et al. 1997). The total area of mangroves in this region is 27,995 km^2 which represents 16% of the global mangrove area (Table 2.1). Aridity and freshwater influence are the major factors controlling mangrove distribution and development in the region (Mitsch and Gosselink 1993). Coastal people depend on mangrove forests for firewood, timber for construction, fishing, and shellfish harvesting. Mangrove wood also is used extensively as firewood in the production of salt. It appears that mangroves in West Africa are threatened by over-cutting, conversion of land for agricultural purposes, and by pollution in areas where oil is being produced (Spalding et al. 1997).

East Africa and the Middle East are dominated by arid coastlines and so, despite having long coastlines, the region has a relatively small area of mangroves. The total area of mangroves in this region is 10,024 km^2 which represents 5% of the global mangrove area (Table 2.1). The harsh environmental conditions, i.e., high salinities, minimal freshwater inputs, and hot and cold temperature extremes, are responsible for the low diversity and relatively low total areas in the Arabian Peninsula (Spalding et al. 1997). Typically, these mangroves are stunted and cannot be used for timber, but are traditionally used for grazing and firewood. On the Indian Ocean islands, the development of mangroves is variable and is related to either the morphology of particular islands or to their isolation (Spalding et al. 1997). Kenya, Tanzania, Mozambique and the western coast of Madagascar, have the best developed mangroves of this region in terms of area, species diversity, and forest structure. Coastal populations are often not large and there is little pressure to convert mangroves to other uses. However, mangrove areas have been lost to urbanization, degradation due to salt production, overgrazing, unsustainable collection of fuelwood, or pollution from oil or urban sources. It is anticipated that population growth in some areas will increase these pressures (Spalding et al. 1997).

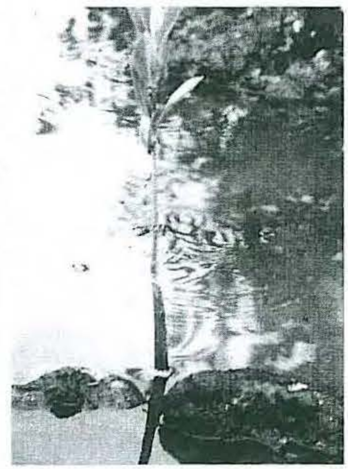
SITE REQUIREMENTS AND MANGROVE ADAPTATIONS

To develop, mangrove forests require adequate protection from wave action. Several physiographic settings favor the protection of mangrove forests, including protected shallow bays, protected estuaries, lagoons, the leeward sides of peninsulas and islands, protected seaways, and behind offshore shell or shingle islands (Mitsch and Gosselink 1993). The range and duration of flooding tides also exert a significant influence over the extent and functioning of the mangrove forests. Tides are important to mangroves, importing nutrients, aerating the soil water, and stabilizing soil salinity. Most mangroves are found in a tidal range of 0.5 to 3 m and more (Mitsch and Gosselink 1993). However, mangrove vegetation, particularly the dominant trees, has several adaptations that allow it to survive in environments characterized by occasional harsh weather, high salinity, and anoxic soil conditions.

Saltwater is not necessary for the survival of any mangrove species, but gives mangroves a competitive advantage over vascular plants that do not tolerate salt (Mitsch and Gosselink 1993). Seasonal oscillations in soil salinity are a function of the height and duration of tides, the seasonality and intensity of rainfall, and the seasonality and amount of freshwater that enters the mangrove forests through rivers, creeks, and runoff. The ability of mangroves to live in saline soils depends on their ability to control the concentration of salt in their tissues. Mangrove trees can prevent salt from entering the plant at the roots (salt exclusion) and excrete salt from the leaves (salt secretions) (Mitsch and Gosselink 1993). Some authors mention leaf fall as another mechanism for discharging salt and argue that it could be of significance because mangroves produce essentially two crops of leaves per year (Spalding et al. 1997). Although mangroves are adapted to saline and brackish environments, the high salinity in some arid regions can restrict their growth.

Anoxic conditions exist in most mangrove soils when they are flooded. The degree of anoxia depends on the duration of flooding, the freshwater influence, and tidal flows accessible to the mangrove (Mitsch and Gosselink 1993). When creeks and surface runoff pass water through mangrove forests, the reduced conditions are not as severe because of increased drainage and continual import of oxygenated waters. Mangrove soils are often acidic, resulting from highly reduced conditions and the subsequent accumulation of reduced sulfides. Soils in mangrove areas are fine grained, often semi-fluid and ill-consolidated, with abundant humus composed largely of the remains of roots and other woody structures (MacNae 1968). Mangroves survive in these anoxic conditions by developing prop roots, drop roots, and small pneumatophores (Fig. 2.1, 2.2). Oxygen can enter the plant through small pores, called lenticels, that are found on both pneumatophores and on prop and drop roots. When lenticels are exposed to the atmosphere during low tide, oxygen is absorbed from the air and some of it is transported to and diffuses out of the roots through a system of aerenchyma tissues (Mitsch and Gosselink 1993). This maintains an aerobic micro-layer around the root system. When the prop roots or pneumatophores of mangroves are continuously flooded, mangroves soon die.

Another adaptation mangrove trees have developed is viviparous seedling. The seeds or propagules germinate while they are still on the parent tree without the intervention of a resting stage. This allows increased seedling success where shallow anaerobic water and sediments would otherwise inhibit germination (MacNae 1968). Once ripe, propagules will eventually fall and root if they land on sediments or will float and drift with currents if they fall into the sea. After a time, if the floating seedling becomes stranded and the water is shallow enough, the seedling will attach to the sediments and take root (Fig. 2.3). It is not well understood whether the contact with the sediments stimulates the root growth or if the soil contains chemical compounds that promote root development (Mitsch and Gosselink 1993). Floating seedlings also are important in mangrove dispersal and invasion of newly exposed substrates.


Clockwise from top left:
Figure 2.1. Numerous prop roots of *Rhizophora mangle* with young trees successfully established behind this natural barrier.
Figure 2.2. Pneumatophores of *Avicennia spp.*
Figure 2.3. Young seedlings of *Rhizophora mangle* stranded in shallow water.

TYPES OF MANGROVES

Mangrove forests follow rather than precede the silting up of a coastal area and accelerate the accumulation of mud or other soil. The development of mangroves is affected by topography, substrate, and freshwater hydrology as well as tidal action. Mitsch and Gosselink (1993) reviewed the classification of mangrove ecosystems according to their physical conditions:

- **Fringe mangroves** are found along protected shorelines and along some canals, rivers, and lagoons. They are common along shorelines adjacent to land higher than mean high tide but are exposed to daily tides. They tend to accumulate organic debris because of the low-energy tides and the dense development of prop roots. Because these sites are open, fringe mangroves are often exposed to storms and strong winds that lead to the further accumulation of debris. The fringe forests are dominated by mangrove species with a prop root system that obstructs the tidal flow and dissipates wave energy during periods of heavy seas. These mangroves are particularly sensitive to the effects of ocean pollution.
- **Riverine mangroves** are found along the edges of coastal rivers and creeks, often several miles inland from the coast. These mangroves may be dry for a considerable time, although the water table is generally just below the soil surface. They are affected by upland freshwater runoff and the adjacent river and can sometimes be significantly influenced by upstream activity or stream alteration. The combination of adequate freshwater and high inputs of nutrients from both upland and estuarine sources causes these forests to be generally very productive, supporting large (16-26 m tall) mangrove trees. Riverine mangroves export a significant amount of organic matter because of their high productivity. Salinity varies but is usually lower than that of other mangrove ecosystems.
- **Basin mangroves** occur in inland depressions or basins, often behind fringe mangrove forests, and in drainage depressions where water is stagnant or slowly flowing. These basins are often isolated from all but the highest tides and yet remain flooded for long periods once tide water does flood them. The ground surface of such forests is often covered by pneumatophores from the dominant trees.
- **Dwarf or scrub mangroves** are examples of isolated, low-productivity mangrove wetlands that are usually limited in productivity because of the lack of nutrients or freshwater inflows. Dwarf mangroves are dominated by scattered, small (often less than 2 m tall) mangrove trees. Hypersaline conditions and cold at the northern extremes of the mangroves range can also produce "scrub" or stressed mangrove trees in riverine, fringe, or basin mangroves.

ZONATION

Distribution of mangrove trees and their zonation is the result of the interactions between the frequency of tidal flooding, physico-chemical characteristics and, water-logging of the soil (MacNae 1968). All of these parameters are in turn modified by the presence of creeks, rivers, and channels and the amount of rainfall, evaporation, and transpiration. Mitsch and Gosselink (1993) described a typical zonation as follows:

> *Rhizophora* is found in the lowest zone, with seedlings and small trees sprouting even below the mean low tide in marl soils. Above the low tide level but well within the intertidal zone, full-grown *Rhizophora* with well-developed prop roots predominate. Tree height is approximately 10 m. In the general public mind this zone is visualized as the typical mangrove forest dominated by arching prop roots making passage difficult. Behind the *Rhizophora* zone and the natural levee that often forms in fringe mangroves, basin mangrove wetlands, dominated by *Avicennia* and *Bruguiera* with numerous pneumatophores are found where flooding occurs only during high tides. There is usually a transition zone between the mangrove zones and upland ecosystems where flooding occurs only during spring tides or during storm surges and soils are often brackish to saline. At this most landward margin, it is common to find stands of *Lumnitzera* and *Xylocarpus*.

Variation in development of these zones is to be expected. In general, a complete zonation will only be found in an area with a considerable intertidal range, with an excess of water availability over loss by evaporation and transpiration in all seasons, and where silt in suspension is available to ensure that deposition of mud on the surface of the soil is always raising the soil level and enabling the mangrove to extend seaward (MacNae 1968). Succession can sometimes be hard to recognize because of human interference.

Zonation of mangrove trees is predominantly regulated by tidal flooding. The zones will vary in width with the nature of the slope of the shore and with the range of the tide. Variation in tidal inundation influences a number of edaphic factors including soil redox potential, salinity, pH, and concentrations of nutrients and phytotoxins such as sulfide that are known to influence growth and distribution of mangrove vegetation (McKee 1995). In addition, biotic factors such as seed predation may vary across the intertidal zone and influence mangrove species distribution patterns. Erosion patterns on sea shores are also recognized as an important regulator for mangrove zonation. When a soil is eroded, either by wave action or by current from rivers or tidal channels, species of mangrove will resist differently. Species of *Avicennia* and *Sonneratia* are more vulnerable than species of *Bruguiera* which are more vulnerable than species of *Rhizophora* (MacNae 1968). Hardiness is directly related to the depth of rooting of the different tree species. It will take a slightly longer period to breach a *Rhizophora* zone but once this is done the remainder of the mangrove forest is quickly destroyed merely because the soil is washed from under the trees.

The zonation pattern of parent mangrove trees will in turn regulate seedling development and distribution. Physico-chemical characteristics of the soil, light and nutrient availability, and proximity to reproductive adult trees are all factors determining the spatial patterns and density of seedling (McKee 1995). Seedling establishment along tidal gradients and their success in being stranded depend on propagule characteristics (e.g., size, specific gravity, and flotation), current actions, predation pressure (e.g., by crabs or snails), and their resistance to desiccation. A recent study in Kenya (Van Speybroeck 1992) confirms that propagule dispersal is the result of both "self-planting" and "stranding" factors. "Self-planting" refers to the development of seedlings under the parental trees. "Stranding" refers to seeds and propagules that are washed away by the tidal action and dispersed by the water to anchorage places away from the parental trees. "Self-planting" is the major mechanism of propagule dispersal in undisturbed mangroves, where only the seaward margin is exposed to strong wave action and where the mangrove forest as such provides sufficient protection to prevent uprooting of newly established seedlings in the intertidal zone (Van Speybroeck 1992). On the other hand, "stranding" is more important in places without a direct input of "self-planting" propagules such as in over-exploited or cleared mangrove forests (Van Speybroeck 1992). New seedling protection from wave action is critical in the success of their establishment, because of the risk of strong waves to uproot not-fixed seedlings. After establishment, differential seedling tolerances to physico-chemical conditions, herbivory pressure, light availability, and nutrient concentrations further refine survival patterns and spatial distribution of each species (McKee 1995).

Researchers are still debating the significance of the zonation of plants in mangrove forests (Mitsch and Gosselink 1993). Some consider each zone to be a step in an autogenic successional process that leads to freshwater wetlands and eventually to tropical upland forests or pine forests. Other researchers consider each zone to be controlled by its physical environment to the point that it is in a steady state and represents the optimal and self-maintaining ecosystem for these low-energy, tropical, saline environments (Mitsch and Gosselink 1993). In such a situation high rates of mortality, dispersal, germination, and growth are the necessary tools of survival.

MANGROVE FUNCTIONS IN NATURAL ECOSYSTEMS

Mangrove forests are generally recognized as playing key roles in coastal ecosystems. Researchers have established their importance in serving as habitat to a large fauna and flora, in providing physical stability and erosion control to certain shorelines, in protecting inland areas from severe damage during storms and strong tidal waves, in exporting organic matter to adjacent coastal food chains, and in serving as sinks for nutrients and carbon. Mangroves have also been identified as regulators for adjacent ecosystems, such as terrestrial wetlands, saltmarshes, seagrass beds, and coral reefs (Mitsch and Gosselink 1993).

Mangroves are located in the region between the sea and dry land and so contain many animals and plants derived from both environments. In general, a wide diversity of animals is found in mangrove wetlands. Their distribution sometimes parallels the plant zonation described above (Mitsch and Gosselink 1993). Mangroves provide both shelter and food for resident animals (Lewis 1982). Many of the animals found in mangrove forests are filter-feeders or detritivores. Barnacles and oysters attach themselves to the stems and prop roots of mangrove trees within the intertidal zone and filter organic matter from the water during high tide (Mitsch and Gosselink 1993). Fiddler crabs (*Uca* spp.) and mudcrabs (*Scylla serrata*) are abundant in mangrove wetlands in Southeast Asia, living on the prop roots and high ground during high tide and burrowing in the sediments during low tide (MacNae 1968). Many other invertebrates, including snails, sponges, flatworms, annelid worms, anemones, mussels, sea urchins, and tunicates are found growing on roots and stems in and above the intertidal zone. Birds are maybe the most noticeable inhabitants of mangroves. It is common to observe large flocks of cormorants, herons, or egrets in the evening coming to nest in mangrove forests. Pelicans, ibis, spoonbills, hammer-head, sea eagles, ospreys, kingfishers, woodpeckers, pigeons, and passerine birds are just a few other examples of birds frequently found in mangroves. Because of the aquatic component of the mangrove forests, it is also common to find amphibians and reptiles such as crocodiles, alligators, water snakes, vipers, turtles, and frogs. Other vertebrates that inhabit mangrove swamps include monkeys, macaques, otters, hippopotamuses, wildcats, pumas, rats, mongooses, wild pigs, and bears. Insects are of course common in mangroves. Some bees visit the flowers of *Rhizophora* and *Aegiceras* species and produce honey that is often harvested by coastal people. Mangrove wetlands support a complex aquatic food web and their surrounding waters are often rich in fish and shellfish.

Trapping of particulate materials by mangrove plants is an important sedimentary and biogeochemical process. Studies estimated that accretion in fringe mangroves is less than 1 mm/yr, 1 to 2 mm/yr in basin mangroves, and greater than 2 mm/yr in riverine mangroves (Twilley et al. 1992). Sediments suspended in the water column are deposited in mangroves during flooding, enriching mangrove soils. The extensive root system of mangroves enhances this trapping process and retards the forces of erosion along the shoreline. Although this function has been overstated to the extent of calling mangroves "walking trees", roots do contribute to sedimentation in estuaries (Twilley et al. 1992).

Certain functions of mangrove forests such as primary productivity, organic production, and litter decomposition have been well documented, particularly for southern Florida (Mitsch and Gosselink 1993). Studies have demonstrated the importance of physico-chemical conditions, including solar radiation, temperature, tides, salinity levels, nutrient concentrations, soil type, drainage, oxygen concentration, and pH for the control of these natural functions (Twilley et al. 1992). The individual plant species present in the intertidal zone can also affect patterns of productivity, because some plants have growth rates that are intrinsically higher than others. Table 2.2 summarizes daily productivity and litter production data for riverine, basin, and scrub mangroves from a number of field studies. It is important to notice that the productivity values given in Table 2.2 are averages for Florida and that due to difficulties in measurement, productivity values can be extremely variable (Field 1996). Gross and net primary productivity is the highest in riverine mangroves, intermediate in basin mangroves, and the lowest in dwarf mangrove stands. Higher productivity at the riverine site can be attributed to the greater influence of nutrient loading and freshwater turnover (Mitsch and Gosselink 1993). The same connection (riverine > fringe > basin > scrub) was observed for organic production measured as litter fall; the greater the hydrologic turnover, the greater the litter production is. These data confirm the importance of tides, freshwater runoff, and water chemistry as factors controlling mangrove productivity. Tidal flows and upland runoff will influence water chemistry and hence productivity by transporting oxygen to the root system, by removing the buildup of toxic materials and salt from the soil water, by controlling the rate of sediment accumulation or erosion, and by indirectly regenerating nutrients lost from the root zone (Mitsch and Gosselink 1993). However, salinity level is recognized as a key parameter in mangrove productivity. Mangrove trees put less of their energy into physiological maintenance when the water is low in salts. Respiration generally increases as a metabolic cost of adapting to high salinities (Mitsch and Gosselink 1993). The productivity of a mangrove forest can be very low if the environmental conditions are adverse, but under some conditions it can compare well with upland tropical forests (Spalding et al. 1997). The pattern of zonation of metabolism follows the zonation of species; species that are found growing out of their zone will have lower productivity than those that are adapted to those conditions, and competition will eventually eliminate them from that zone (Mitsch and Gosselink 1993).

Nutrient exchange between mangroves and near-shore waters is poorly understood because of difficulties in measuring nutrient fluxes in coastal waters (Twilley 1988, Rivera-Monroy et al. 1995). It is generally agreed that mangroves are areas of active nutrient transformation and exhibit a net export of detritus (Rivera-Monroy et al. 1995). However, tides and runoff control the exchange of materials across the boundaries of the mangrove-estuarine ecosystem (Twilley 1988). The amount of water transported through mangroves, estuaries, and the continental shelf is dependent on the hydrologic turnover and the geomorphology of the region. The hydrologic turnover of riverine mangroves is high because it is dominated by river flow and tidal inundation, while fringe mangroves are influenced mainly by frequent tidal inundation. Basin mangroves have lower hydrologic turnover because they are located inland of fringe or riverine communities and as a result

TABLE 2.2: PRIMARY PRODUCTIVITY, RESPIRATION, AND LITTER FALL MEASUREMENTS FOR THREE TYPES OF MANGROVE WETLANDS (FROM MITSCH AND GOSSELINK 1993).

	Mangrove Wetland		
	Riverine	Basin	Scrub
Gross primary productivity[a] (kcal m^{-2} day^{-1})	108	81	13
Total respirationa (kcal m^{-2} day^{-1})	51	56	18
Net primary productivity[a] (kcal m^{-2} day^{-1})	57	25	0
Litter production[b] (kcal m^{-2} day^{-1})	14 ± 2	9.0 ± 0.4	1.5

[a]From several sites in Florida; based on CO_2 gas-exchange measurements; assumes 1 g organic matter = 4.5 kcal.
[b]Average ± standard error from several sites in Florida and Puerto Rico; measured with litter traps; assumes 1 g organic matter = 4.5 kcal.

are less frequently inundated by either tides or river floods. Rates of organic export from basin mangroves are dependent on the volume of tidal water inundating the forest each month, and accordingly export rates are seasonal in response to the seasonal rise in mean sea level (Rivera-Monroy et al. 1995). Rainfall also increases organic carbon export from mangroves, especially dissolved organic carbon. As hydrologic turnover increases, both the magnitude of litter produced within mangroves and the proportion of the litter that is exported increase (Twilley 1988). Estimates of net ecosystem production between a fringe and basin mangrove suggest that a large proportion of the net primary productivity in the more inundated forests is exported, while in basin forests more of the net production is accumulated or utilized within the system.

The idea that intertidal wetlands may be a nutrient sink is particularly confusing because it contradicts the "outwelling" concept of detritus exchange for mangroves established above (Twilley 1988). A study of a fringe mangrove showed that there was an uptake in dissolved inorganic nitrogen from the tidal creek and an export of particulate nitrogen to the tidal creek (Rivera-Monroy et al. 1995). Thus, this particular mangrove forest contributed detritus to the estuarine water column and served as a sink of inorganic nutrients. Studies indicate that mechanisms which conserve nutrients may vary along a tidal continuum (Twilley 1988, Twilley et al. 1992, Rivera-Monroy et al. 1995). In areas of high tidal frequency, higher recycling efficiency may occur in the canopy whereas in lower tidal activity, nutrient recycling may occur on the forest floor. The importance of the total flux of detritus from mangroves to the organic matter budget of estuarine ecosystems depends also on the relative size of both systems. It has been suggested that the ratio of mangrove area to the surface water area of estuaries may be indicative of the importance of mangroves to the productivity of aquatic ecosystems (Twilley 1988). Field (1996) concluded that generally where the amount of mangrove forest area is high compared to the area of open water, then mangrove production is the major source of carbon entering the aquatic food chain. Probably only in large lagoons with thin strips of mangrove at the edges of the water is the production of carbon by other sources, such as phytoplankton, greater than that produced by the mangroves (Field 1996). Using a technique involving the measurement of $^{13}C/^{12}C$ ratios of organic matter, Fleming et al. (1990) found that mangroves were providing 37% and seagrass 63% of the carbon to organisms in an adjacent bay, suggesting that mangrove detrital export is important to offshore water only in regions local to the mangrove forests and that it may be unimportant relative to other carbon sources farther offshore.

Potentially, the export of organic matter from mangroves can stimulate aquatic primary productivity, sustain secondary productivity in estuarine and coastal waters, and buffer inputs of nutrients and other materials from terrestrial sources (Rivera-Monroy et al. 1995). Studies in south Florida reported that about 50% of the above-ground productivity of a mangrove forest was exported to the adjacent estuary as particulate organic matter (Mitsch and Gosselink 1993). Examination of stomach contents of estuarine animals showed that mangrove detritus is the primary food source in the estuary. These primary consumers of mangrove litter serve in turn as food to game fish and commercial fisheries species (Mitsch and Gosselink 1993). These findings led to the reasonable extrapolation that mangrove detrital export is important to offshore water and that litter produced in the canopy of mangrove forests represents an important source of nutrients to the foodweb of adjacent coastal waters (Twilley et al. 1992). This theory led then to the statement that the removal of mangrove forests would cause a significant decline in sport and commercial fisheries in adjacent open waters. The theory is further supported by the fact that mangrove ecosystems (mainly fringe and riverine mangroves) have been documented as important nursery areas and sources of food for sport and commercial fisheries (Mitsch and Gosselink 1993). However, there is no direct evidence of a cause and effect relationship for mangroves and fisheries (Twilley 1988). Evaluating the importance of mangroves to sustaining secondary productivity in estuarine and coastal ecosystems depends on the transport and utilization of organic matter from mangroves and on the type of mangrove. Considering mass balances, some mangrove-estuarine ecosystems transport substantial amounts of organic material to estuarine and coastal waters. However, the mass balance approach does not indicate directly the utilization of this material by higher trophic levels (Twilley 1988).

MANGROVE USES AND VALUES

Historically, human pressure on the mangroves has been limited and, except for some subsistence populations, the people saw mangrove areas as inhospitable, unhealthy, and dangerous (Field 1996). Mangrove forests are not easy places to penetrate and few communities of people actually live within the mangroves (Kunstadter 1986) but many people live in close proximity. During the last sixty years, the pressures of increasing population, shortage of productive lands for agriculture in tropical countries, and industrial and urban development have led to a significant proportion of the world mangrove resources being consumed (Field 1996). The International Union for Conservation of Nature (IUCN 1983) estimates that as much as 50% of the original mangrove extent has been lost. Today, mangroves are logged for timber, fuelwood, leather tanning, and charcoal production, chipped for paper production, and reclaimed to provide land for agriculture, aquaculture, and the construction of mines, ports, tourist resorts, and housing (Fig. 2.4). Natural disasters including typhoons, tropical cyclones, hurricanes, drought leading to hypersaline conditions, and microbial diseases, are also important factors controlling mangrove abundance (Mitsch and Gosselink 1993).

Figure 2.4. Intense coastal development in a former mangrove area, Manila Bay, Philippines.

There is a general agreement that the global area of mangroves is declining (Field 1996), although some regions may have seen a net increase in mangrove coverage. For example, observations of area photographs and old maps show an increase in mangrove development over the last 150 years in the Sinu River estuary on the Caribbean coast of Colombia. It is thought that exploitation of upland forests, increase in soil erosion, and subsequent increase in coastal accretion allowed the development of mangroves in this particular estuary (J.V. Mogollon Velez, Minister of the Environment, Colombia, personal communication). This example illustrates the highly dynamic nature of mangrove wetlands and the fact that a precise figure on mangrove loss is often restricted to the region concerned. In 1982, Ong (1982) estimated that the rate of mangrove destruction in Malaysia was around 1% per year. Obtaining estimates of decline for other areas of the world is difficult but it is probably reasonable to assume that the rate of decline in the Asia-Pacific region is the highest (Lewis 1982, Spalding et al. 1997). Lewis (1982) gave a list of available figures for documented losses (Table 2.3). The list is quite short because most of the data on mangrove losses have not been gathered in scientific publications or systematic studies, but result mainly from anecdotal information. Numbers can be made to say many things, but they will never account for all the real social and environmental problems emerging from mangrove losses. There is little comfort in a number indicating a small proportion of mangrove loss if the region of interest is seriously affected by the wetland destruction. However, the increasing area of mangrove restoration sites in some regions is worthy of note. Reforestation areas in Bangladesh, Vietnam, and Pakistan now cover over 170,000 ha, while Cuba is reported to have planted around 25,700 ha of mangroves (Field 1996).

TABLE 2.3: REPORTED MANGROVE LOSSES (FROM LEWIS 1982).

Location	Original area cover (ha)	Existing area cover (ha)	Loss (%)
USA, Florida			
Tampa Bay	10,053	5,630	-44
Biscayne Bay	63,300	11,100	-83
Puerto Rico			
Main Island	24,300	6,405	-74
Vieques Island	446	367	-18
Australia			
Botany Bay	1,500	1,000	-33
Southern Vietnam	286,400	104,123	-64

TIMBER. Mangrove timber was and still is widely used by coastal communities. Mangrove genera producing valuable timber are *Avicennia, Bruguiera, Ceriops, Heritiera, Rhizophora, Sonneratia*, and *Xylocarpus* (MacNae 1974). Mangrove trees are cut and used as stakes for shore-based fish traps, parts of canoes and boats, poles, posts for building construction, source of bark for tannin extraction, and firewood for daily cooking needs or used in the production of salt (MacNae 1974, Thorhaug 1988, Ngoile and Shunula 1992, Mitsch and Gosselink 1993). *Rhizophora mucronata* and *Ceriops tagal* are the two preferred species for tannin extraction in Africa and Madagascar (MacNae 1974). The bark is stripped off the trees (Fig. 2.5), pounded and mixed with lime, and soaked in metal or concrete troughs into which animal skins are immersed and left to soften for one or two weeks (Ngoile and Shunula 1992). However, commercial exploitation of tannin from mangrove trees seems unable to compete with that from acacia and its practice is declining (Mitsch and Gosselink 1993). In Asia and Africa, the leaves of the mangrove palm tree, *Nypa fruticans*, are extensively used for thatching and house building (MacNae 1974). Sometimes the inflorescences of the palm tree are tapped for sugar and for alcohol production (MacNae 1974). *Xylocarpus granatum* and *Heritiera littoralis* are used in Africa for medicinal purposes. A powder obtained from the seed coat from both species is dissolved and orally administered for the treatment of abdominal ailments (Ngoile and Shunula 1992).

The most consumptive use of mangrove timber today is for firewood, charcoal, and paper production (MacNae 1974, Ngoile and Shunula 1992, Mitsch and Gosselink 1993). For these purposes, the Rhizophoraceae are preferred. In most of

Figure 2.5. Mangrove bark used in tannin extraction.

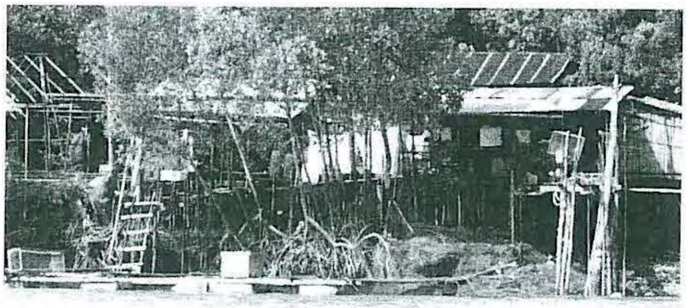


Figure 2.6. Fishermen settlement inside a mangrove forest where fish cage culture is also practiced.

Figure 2.7. Mud crab farming in Ranong, Thailand.

Southeast Asia, forest management procedures and silvicultural rotation are implemented to ensure sustained production and maximum economic yield of the tree species of choice (Field 1996). For example, in compliance with the Indonesian Mangrove Silvicultural System, logging activities in Indonesia will have a rotation cycle of 30 years (Field 1996). Only trees that reach a diameter at breast height (dbh) of 10 cm or more are allowed to be cut and forty trees per hectare are left intact to function as seed producers and allow sufficient natural regeneration. Observations in the field suggest that these seed producers should be distributed in groups of four to five trees, instead of being distributed equidistantly from one tree to the next, to be able to withstand strong wind. Indonesian regulations also call for a 130-meter strip of mangroves at the seaward edge along the coastline and a 50-meter strip along the riverbank to be left undisturbed (where available) to function as greenbelts (Field 1996). These greenbelts maintain primordial functions such as protection of shorelines and natural habitat for fish and shellfish. Field (1996) concluded that silviculture success will depend on various factors of which the most important are the accessibility of the forest and consequent removal of timber, and then the ease and degree of regeneration, either natural or encouraged by planting. For these reasons, mangrove forests commercially exploited for timber will be divided into mangrove strips by canals and cut out by rotation when the trees reach an economic size.

FISHING. Artisanal and commercial fishing take place either within or in the vicinity of the mangrove stands and some coastal communities depend solely on these resources to supplement protein (Fig. 2.6; MacNae 1974, Turner 1977, Kunstadter 1986, Ngoile and Shunula 1992). The mudcrab of mangrove wetlands, *Scylla serrata*, is considered to be a great delicacy (MacNae 1974). In some parts of Asia, an industry of fattening crabs is expanding (Fig. 2.7). In Singapore, small crabs of 5 cm in diameter are caught in creeks in local mangroves or in adjacent waters, placed for fattening in cement tanks where they are fed on trash fish or offal until they have reached a marketable size (MacNae 1974). Females, being larger than males, fetch higher prices. In addition to the conventional fisheries, molluscs are also harvested from mangrove areas. The large bivalve *Geloina* is harvested for local consumption from India to Australia (MacNae 1974). In Africa and Madagascar, *Pyrazus* sp., *Pinctada* sp., *Modiolus* sp., and *Crassostrea* sp. are all molluscs harvested by coastal people (Ngoile and Shunula 1992). Sometimes, these molluscs are then used as bait for fishing, but more often they are harvested for local consumption (MacNae 1974, Ngoile and Shunula 1992). In Oman, turtles found in mangroves are hunted for their meat, shell, and oil. Fishermen never hesitate to catch a sea turtle during their fishing trips and collect their eggs for food and medicinal purposes (Fouda and Al-Muharrami 1995). The human pressure on these natural resources has increased over the last decades. In some regions, the combination of traditional harvest and commercial exploitation has reached unsustainable levels and is considered an important cause for the collapse of subsistence fisheries along the Eastern coast of Africa and in some parts of Southeast Asia.

Estuaries and lagoons are used by species of fish and crustaceans for feeding, reproduction, and as nursery grounds (MacNae 1974). Like crustaceans and molluscs, many species of fish are closely associated with mangroves but few are truly mangrove residents (MacNae 1974, Primavera 1993). Qualitative and quantitative data on the importance of mangrove wetlands to commercial fisheries are difficult to find, but ressearchers often agree that mangrove areas are important refuges for many varieties of fish at a time when they are particularly vulnerable to predators. Some genera seem characteristically to inhabit estuaries and these genera may contain fish and crustaceans of commercial value, including among others clupeids, mullets, catfishes, Indian shad, milkfish, tilapia, prawns, and penaeid shrimps (MacNae 1974). An analysis of the 1981 landings in Malaysia shows that 32% may be associated with mangroves, while in the Philippines, 72% of the catch from 1982 to 1986 has some close association with mangroves (Primavera 1993). In Florida, USA, about 80% of the marine commercial and recreational catches are dependent on mangroves for at least some critical stages of the species life cycle (Lewis 1982, Primavera 1993).

Scientists often argue that there is a positive relationship between commercial yields of fish and crustaceans and the area of intertidal vegetation (i.e., vegetated salt marsh with macrophytes and/or mangrove trees). Lewis (1982) reports a 20% decline in commercial fisheries catches along Florida's Gulf Coast after two peaks of around 60,000 tons in 1960 and 1965. During the same period, 40% of the mangroves of one main estuary (Tampa Bay) in the area was lost to residential and commercial development (Lewis 1982). Turner (1977) found that, on a regional basis, annual shrimp yields inshore are directly related to the area of estuarine vegetation whereas they are not correlated with the area, average depth, or volume of estuarine water. The analysis of the data coming from 27 locations worldwide supported the hypothesis that the abundance and type of commercially valuable quantities of penaeid shrimp are directly related to the absolute area and the type of estuarine-intertidal vegetation. Turner (1977) concluded that the good correlation with the measurement of intertidal areas results from the fact that it is an indirect measurement of penaeid shrimp habitat, and that substrate selection is an important process affecting shrimp distribution. Often, correlation between mangrove losses and decline in fisheries is complicated by other human impacts such as overfishing. DeSylva and Michel (1975, as reported in Lewis 1982) were unable to demonstrate conclusively that the partial or complete defoliation of 104,123 ha of mangroves in South Vietnam permanently damaged the estuarine ecology of the area, although they noted increased turbidity and erosion because of the lack of vegetative cover and a dramatic decrease in fisheries harvests. In this particular example, it was not possible to separate overfishing impacts from social and/or defoliation causes (Lewis 1982).

PONDS AND AGRICULTURE. For centuries in Java and the Philippines, mangrove wetlands have been transformed into ponds (known in Java as tambaks) for the cultivation of finfish, penaeid shrimp, and prawn (MacNae 1974). In Java the species cultivated most commonly is *Chanos chanos* (milkfish) which breeds just offshore in shallow water of sandy bays. MacNae (1974) reports a highly divided labor distribution in milkfish culture: fry are collected by one group of people, transported to the ponds by a second group of people, and a third group of people rears the fry to marketable size. The pond caretakers often live in houses built on the banks and dispose of human and domestic animal excrement in the ponds (MacNae 1974). Ponds are generally 0.5 to 2 ha in area, narrow in shape, and communicate by way of sluice gates with a system of tidal canals. The average milkfish production in Indonesia is around 400 to 500 kg/ha per year (MacNae 1974). Culture of shrimp and prawn is more recent and not restricted to Southeast Asia. Culture types and intensities will be discussed in more detail in the next chapter.

Over the centuries, mangrove forests have also been cleared for agriculture. In Africa, it is common to find tree crops in former mangrove areas, the most important of which are cashewnuts, mangoes, and coconuts (Gang and Agatsiva 1992). Coconuts are very much valued in Kenya and provide essential items such as cooking fat, fuelwood, building materials, extract for local beer, and oil for hair (Gang and Agatsiva 1992). In Asia, some mangroves have been cleared for paddy-field cultures (MacNae 1974) or transformed into rubber and palm oil plantations (Pongthanapanich 1996). Direct grazing of livestock on mangroves is practiced in the Sundarbans of the Ganges and Brahmaputra River deltas of India and Bangladesh (Siddiqi and Khan 1996, Untawale 1996). Leaves of *Avicennia* are comparable in nutritive value to alfalfa, and in Asia, mangroves have served over the years as fodder and green manure for livestock. In areas with a strong difference in seasonal climate, cleared mangroves and dried out areas are made into a series of shallow evaporation ponds for salt production, called 'salinas' in East Africa. Salt also may be extracted from mangrove plants in the humid tropics. Rhizomes of *Nypa* palm are allowed to stand in seawater to absorb salt, they are then burned, and salt is extracted from the ash (MacNae 1974). This procedure is quite destructive for mangroves because large quantities of fuelwood are required. Salt production in salinas in Mozambique varies between 15 and 40 tons of salt per hectare at a value of US$16 to US$18 per ton (MacNae 1974).

ECOLOGICAL FUNCTIONS AND VALUES. Benefits of mangrove wetlands are not limited to their various direct uses, but also result from some of their ecological functions and values. A list of ecological functions of mangrove includes: wildlife habitat, fish and crustaceans habitat, sediment trap, flood mitigation, storm protection, prevention of saline intrusion, nutrient export, support of complex aquatic foodwebs, removal of nutrients and toxicants. More recently, the biological diversity of mangroves has been recognized, and areas for research, education, conservation, and tourism have been allocated.

These various direct and indirect values of mangroves have long benefited coastal communities. It is then tempting to establish an overall economic value of mangrove wetlands to help decision makers in their assessment of the best possible use(s) for these limited resources. Table 2.4 summarizes the various economic values of mangroves. Difficulties in measuring the true economic value of mangrove arise because some products or services do not have market prices and the goods and services produced occur both within and outside the mangrove (Primavera 1993). In addition, that different types of mangrove will have different ecological significance makes it difficult to generalize. To a large extent, the within-mangrove, on-site goods and services are land based, while the off-site effects are usually aquatic or coastal (Table 2.4). When the value of an existing mangrove forest is assessed, the analysis traditionally has included only those marketed items like poles, charcoal, woodchips, crabs, and oysters (Primavera 1993, Hambrey 1996). As knowledge has been gained on the interaction between mangroves and adjacent coastal waters, greater attention has been paid to services that occur off-site and that are marketed (e.g., fish and shellfish caught in coastal waters). Other less tangible values such as biodiversity, physical protection, or importance for subsistence and in local economy are not addressed systematically in economic studies (Primavera 1993, Hambrey 1996). Nevertheless, these contributions may be quite important in terms of the total benefits produced by the mangrove ecosystems and deserve a full and comprehensive description in economic evaluations (Hambrey 1996). In a recent study, Constanza et al. (1997) give a total value for mangrove ecosystems of US$11,029 per hectare per year, with a range of US$1,106 to US$24,210. The United Nations Environment Program has placed an annual value of US$215,000 per hectare on mangroves and seagrass beds (Thorhaug 1988). This last estimate appears too high.

TABLE 2.4: APPLICATION OF ECONOMIC VALUES OF MANGROVE GOODS AND SERVICES ACCORDING TO TYPES AND LOCATION (MODIFIED FROM PRIMAVERA 1993).

	Location of goods and services	
	On-site	**Off-site**
Marketed	**Usually included in economic analysis (e.g., poles, charcoal, wood chips, crabs, and oysters)**	**May be included (e.g., fish and shellfish caught in adjacent waters)**
Non-marketed	**Seldom included in economic analysis (e.g., medicinal uses, domestic fuelwood, fish nursery area, wildlife sanctuaries, biodiversity attributes, education, and research)**	**Usually ignored (e.g., nutrient flows to estuaries, buffer to storm damage)**

To illustrate the complexity in establishing a value for mangrove services, I will use catch fisheries as an example. Fishery and marine products, both within the mangrove and in nearby waters, are frequently much more valuable than forest products. Primavera (1993) reports an annual economic value range for forestry products of US$10 to US$400 per hectare and of US$125 to US$2,000 per hectare for fishery products. However, Hambrey (1996) warns against direct estimates of the total value of the offshore fishery divided by the area of mangrove on nearby coast and considers them misleading. The economic benefit is calculated as the fisheries catch associated with mangroves and then frequently multiplied several orders of magnitude to account for the nursery function of the habitat (Thorhaug 1988). These estimates assume that the bulk of nurseries is found in mangrove. In fact, many nurseries are in shallow coastal waters, estuaries, lagoons, and seagrass beds which may or may not be associated with mangroves (Hambrey 1996). In addition, most studies of fisheries in mangroves or seagrass beds do not preclude the presence of the other habitat, although they center on the primary habitat (Thorhaug 1988). Hambrey (1996) further cautions against extrapolation from these general estimates because all mangroves should not be regarded as equal in value. It is evident that the nursery function of mangrove will vary with the penetration of coastal currents, the local hydrography, the physico-chemical conditions, and the ecological importance of the type of mangrove considered. Thorhaug (1988) insists on the fact that the nursery function of a dense, large, intertidal mangrove swamp is far greater than for a thin, patchy layer of shoreline mangroves. A similar assertion can be made for the importance of mangrove outwelling and its role in supporting adjacent coastal foodwebs.

TABLE 2.5: GROSS ECONOMIC VALUES OF MANGROVES FOR FISHERIES BASED ON VALUES OF LANDINGS (FROM KAPETSKY 1985, IN THORHAUG 1988).

Country/Region	Value in US$	Basis for value measurements	Year of estimate	Principal genera
PANAMA				
Gulf of Panama	26,350 per km	Value per km of mangrove shoreline	1978	*Penaeus, Trachypenaeus*
Gulf of Panama	65,164 per km	Value per km of mangrove shoreline	1978	*Cetengraulis, Mysticatus*
Gulf of Panama	3,114 per km	Value per km of mangrove shoreline	1978	*Micropogon, Tutlanus, Cantropomus*
BRAZIL				
Cururuca Estuary	76,886 per km^2	Include only finfishes. Value based on area extent of open water	1981/82	*Mugil, Canyactemus, Macrodon, Sagra, Macropengenisa*
MALAYSIA				
Sabah	133 per km^2	Value based on area extent of mangroves	1977	*Scylla serrata*
Peninsula	277,235 per km^2	Value based on area extent of mangroves, plus estuaries and lagoons	1979	*Penaeus, Scolopherus, Pampus, Polynemus, Lucjanus*
THAILAND				
Khiung District	3,000 per km^2	Value of fishery products captured inside the mangrove system	1977	*Lita, Eleutheroneus, Arias, Ophichchus, Lates*
Khiung District	10,000 per km^2	Value of mangrove-associated species caught elsewhere	1977	*Penaeus*
BANGLADESH				
Sundarbans	2,076 per km^2	Value based on mangrove area plus open water area	1982/83	*Hilsa, Penaeus*
PAPUA NEW GUINEA				
Gulf Province	426 per km^2	Value of shrimp caught outside the mangroves, and of subsistence fishing and crabbing inside	1977	*Penaeus, Metapenaeus, Scylla serrata*, Ambassids, Gobies, Gudgeons, Catfishes

For information, Table 2.5 gives variable estimates of economic values of mangroves based on values of fisheries landings.

Amidst these difficulties in estimating the 'true' economic value of mangrove systems to society, results from such studies could give general directions concerning decision processes related to mangrove management. Often, traditional patterns of land ownership and land use were not recognized by authorities and mangroves were considered as wastelands with low intrinsic values (Kunstadter 1986). It was then an easy decision to turn mangroves over to new owners or concessionaires for more "efficient" economic exploitation. Exploitation of such mangrove areas caused not only ecological degradation but was also responsible for negative socio-economic impacts (Bailey 1988). Although commercial exploitation of mangroves provided wage-labor opportunities for local communities, it often did not support as many people as were supported by traditional land-use systems and often restricted the access to traditional mangrove areas (Kunstadter 1986). Such impacts were felt stronger in areas where the removal left coastal communities without alternative means of employment or food collection (Bailey 1988).

The complexity of evaluating and managing mangroves makes government intervention essential if mangroves are to be used rationally (Kunstadter 1986, Thorhaug 1988, Hambrey 1996, Pongthanapanich 1996). For example, the utilization of mangroves in Thailand is guided by a Cabinet Resolution (15 December 1987) which classifies mangroves into 3 zones (Pongthanapanich 1996): conservation zone, economic zone A, and economic zone B. The conservation zone is kept as a natural forest and is associated with a high conservation value. It covers 43,200 ha or 12% of the total mangrove coverage in Thailand. The economic zone A allows for forest utilization under a sustainable yield basis, mainly for wood concession or conservation. It covers 200,000 ha or 53% of the total mangrove area of the country. Finally, the economic zone B is an area of low value or degraded mangrove where other forms of exploitation are allowed, including conversion to agriculture, salt production, urban or industrial development, and aquaculture. This last zone covers 129,600 ha or 35% of the actual mangrove coverage in Thailand. Indonesia and Vietnam have asked for maintenance of greenbelts or buffer zones along shorelines to protect coastal areas from storms and erosion. However, in many countries mangrove sites associated with high values have not been identified. The process of mangrove zoning may not be easy but is considered a critical step in reducing conflicts among the many mangrove uses. Hambrey (1996) recommends that any zoning which might be introduced to facilitate a more rational and planned development of the industry should be very simple.

Mangroves now appear to be affected by the same processes associated with modernization and economic development that have led to the rapid loss of other types of forest in the tropics. These include rapid growth of human population, expansion of agricultural land-use, use of modern earth-moving machinery and other new harvesting technologies, growing demands for raw materials and for food (especially high-quality animal protein), and an increase in urbanization and industrialization (Kunstadter 1986, Field 1996). Other serious threats are indirect effects of human activities, such as agricultural runoff, industrial pollution, and hydrological alterations.

MANGROVES AND SHRIMP AQUACULTURE

OVERVIEW OF SHRIMP AQUACULTURE

IN THE NATURAL ENVIRONMENT, most shrimp mate in the open ocean and the females spawn 100,000 eggs or more at a time. The eggs hatch into nauplii, the first larval stage, within 24 hours. During the next 12 to 16 days, the larval shrimp changes from a nauplii, to a zoea, and finally to the mysis stage. The larvae feed on phytoplankton and zooplankton. After mysis stage, the young shrimp metamorphose from larval stages and are called post-larvae or PL. Post-larvae shrimp migrate into the nutrient-rich waters of coastal estuaries where they live as benthic organisms. Once the post-larvae become juvenile and subadult shrimp, they return to the ocean where they mature into adults and mate to perpetuate the life cycle.

Shrimp farming duplicates in ponds the portion of the shrimp life cycle that occurs in estuaries. Production ponds are built in coastal areas where there is a ready supply of brackish or sea water. Post-larvae are caught from the wild or produced in hatcheries and stocked in ponds where they are cultured to market size. Generally, after a growing period of 120 to 150 days, cultured shrimp reach a weight of 13 to 25 g at harvest. Fertilizers and feeds normally are applied to ponds to promote rapid growth of shrimp. Water exchange is commonly employed in ponds to enhance water quality. Mechanical aeration is often used in intensive ponds to supplement natural supplies of dissolved oxygen. Discharge from shrimp ponds during water exchange and at harvest is returned to coastal waters. The type and intensity of management practices used during the production cycle will determine the intensity of culture. Culture techniques normally are classified as extensive, semi-intensive, and intensive (Table 3.1).

In an extensive production system, stocking rates usually are less than 5 PL/m^2, little or no fertilizer and feed are used, water is often exchanged at low rates if at all, and there is no mechanical aeration. Production is seldom greater than 200 to 300 kg/ha per crop and so farmers tend to compensate by constructing large ponds, with some up to 100 ha. Extensive shrimp farming is often referred to as the "traditional" system and is widely practiced in Asia. Farms are generally built on inter-tidal flats or in mangrove areas. In Indonesia, mangrove trees sometimes are retained within the shrimp ponds and the production system is referred to as "silvofishery" (Fitzgerald 1997).

In semi-intensive shrimp culture, 5 to 15 PLs are stocked per m^2. Fertilizers and/or feeds are applied, water may

TABLE 3.1: SUMMARY OF GENERAL INFORMATION ON SHRIMP FARMING INTENSITY.

Variable	Production Level		
	Extensive	Semi-intensive	Intensive
Pond size (ha)	5 to 100	5 to 25	0.5 to 2.5
PL stocking density (PLs/m^2)	5	5 to 15	20 to 70
Management inputs (+ = used, - = not used)			
Stocking	+	+	+
Fertilization	+	+	+ or -
Water exchange	+	+	+
Feeding	-	+	+
Use of chemicals	-	-	+
Aeration	-	-	+
Production of whole shrimp per year (metric tons/ha)	0.5 to 1	1 to 5	5 to 20
Value of crops (thousands of US$/year)	4 to 8	8 to 40	40 to 160
Pond siting	inter-tidal flats	inter-tidal flats and above high tide mark	above high tide mark

Figure 3.1. Intensive shrimp farm located above high tide mark, Ranong, Thailand.

be exchanged at 5 to 10% of pond volume per day, but mechanical aeration is not used. Production may be as high as 2,500 kg/ha per crop, but it is usually less. Semi-intensive ponds tend to be smaller in size than extensively managed ponds and are located both in inter-tidal land, which may include mangrove, and on land located above the high tide mark. Semi-intensive shrimp farming is practiced in Latin America and Southeast Asia.

In intensive shrimp farming, PLs are stocked at 20 to 70 per m^2 (Fig. 3.1). Little fertilizer is used, but large amounts of feed are applied. Water exchange rates may reach 30% of pond volume per day, especially at the end of the production cycle when the daily feed input is at its maximum. However, there is a growing trend to reduce water exchange rates. Aeration typically is applied at 8 to 16 horsepower/ha. Production ranges from 4,000 to 10,000 kg/ha per crop, and generally, two crops are produced per year in tropical regions. The best locations for intensive farms are above the high tide mark where ponds can be easily drained and their bottoms dried between crops. Individual pond sizes are usually less than 1 ha. Intensive shrimp farming is practiced primarily in Asia, Australia, and the United States.

PROFILE OF MAJOR SHRIMP INDUSTRIES

Over the last few years, global landings of shrimp from the capture fisheries have maintained a plateau of around 1.9 million tons (Lucien-Brun 1997). It is generally recognized that aquaculture will play an increasing role in the future in meeting the world fisheries demand for shrimp products (Pillay 1996). After enjoying rapid growth during the 1980s, annual aquaculture production of shrimp leveled off at around 700,000 tons from 1991 onwards (New 1996). Currently, farm-raised shrimp represent roughly 30% of the world shrimp production. Around 90% of the shrimp production is absorbed by three principal markets: the USA (36%), Japan (34%), and Europe (20%).

The principal farmed species are *Penaeus monodon* in Asia and *Penaeus vannamei* in Latin America. The other major farmed species are: *Penaeus stylisrostris* in Latin America (mainly Mexico, Ecuador, and New Caledonia); *Penaeus chinensis* in China and Korea; *Penaeus japonicus* in Japan, Korea, China, Taiwan, and Australia; *Penaeus orientalis* in China; *Penaeus penicillatus* in China and Taiwan; *Penaeus merguiensis* and *Penaeus indicus* in extensive farms throughout Southeast Asia (Lucien-Brun 1997).

Shrimp are farmed in over 50 tropical and sub-tropical nations, but around 75% of the farmed shrimp come from only 10 countries. In 1998, total production of farmed shrimp was 750,000 tons, of which 530,000 tons (71%) came from Asia and 220,000 tons (29%) came from Latin America (Jory 1999). There are noticeable differences between the two regions in term of production systems. In Asia, the majority of the farms are small-scale, family operations (Lucien-Brun 1997). In Latin America, the principal producers are often large, integrated companies with hatcheries, semi-intensive farms, packing plants, and even feed mills (Lucien-Brun 1997). For the majority of these operations, capital investment is national with foreign participation (Lucien-Brun 1997). However, it is difficult to generalize and striking examples in each region contradict what was just mentioned.

Table 3.2 lists the major shrimp farming countries in the world in order of importance: Thailand, Ecuador, India, Indonesia, Philippines, Mexico, Colombia, Honduras, Malaysia, and Panama (Jory 1999). Only Colombia, Thailand, Malaysia, and Philippines have an average annual yield higher than 1,500 kg/ha. It appears, thus, that the majority of the farmed shrimp worldwide are produced under semi-intensive systems. However, it is very difficult to arrive at reliable production data of farmed shrimp: private companies that are engaged in the production of high-value species like marine shrimp, which typically are exported, are obviously reluctant to provide production data; substantial quantities of farmed shrimp are often exported illegally, with amounts under-reported or not reported at all to evade paying tariffs and taxes; many countries typically fail to maintain aquaculture data current, with available data typically being a few years old, and production is often under- or overestimated (Jory 1999).

Since 1988, cultivated shrimp in nearly all producing countries have been afflicted with bacterial and viral infections (Qingyin et al. 1997). The yellow head virus hit Taiwan and China in 1988. More recently the white spot disease has emerged in Asia and the Taura Syndrome Virus in Latin America. In each of these new diseases, a deteriorated environ-

TABLE 3.2: PROFILE OF THE 10 MAJOR SHRIMP FARMING COUNTRIES IN THE WORLD (LAND AREA AND MANGROVE AREA FROM SPALDING ET AL. 1997; AREA OF SHRIMP PONDS, SHRIMP PRODUCTION, AND YIELD FROM JORY 1999).

Country	Mangrove area (ha)	Area of shrimp ponds in production (ha)	Shrimp production in 1996 (metric tons)	Shrimp production (% world's production in 1996)	Yield (kg/ha/year)
Thailand	264,100	70,000	210,000	28	3,000
Ecuador	246,900	160,000	130,000	17	813
India	670,000	140,000	70,000	9	500
Indonesia	4,255,000	200,000	50,000	7	250
Philippines	160,700	20,000	35,000	5	1,750
Mexico	531,500	24,000	17,000	2	708
Colombia	365,900	3,200	12,000	2	3,750
Honduras	145,800	14,000	12,000	2	857
Malaysia	642,400	3,000	8,000	1	2,667
Panama	181,400	8,500	8,000	1	941
TOTAL	**7,463,700**	**642,700**	**552,000**	**74**	**859**

ment may be providing the necessary conditions for growth of pathogens (Qingyin et al. 1997). Many factors contribute to environmental deterioration and the principals among them are little consideration to the ecological carrying capacity of a specific area and pollution from industrial, municipal, or even aquacultural origin.

Shrimp farming generates many direct and indirect jobs in related businesses such as feed manufacturing, processing, transportation, and marketing as well as in construction, engineering, and manufacturing. In Ecuador for example, it is estimated that shrimp farming generates approximately 200,000 direct jobs and 17,000 indirect ones (Lucien-Brun 1997). Rosenberry (1996) reports that the 78 packing plants of Ecuador employ 12,000 people, 80% of them women. To present it from another perspective: a general evaluation of the aquaculture sector in Ecuador reveals that 7% of the active population is employed directly or indirectly in jobs generated by this sector (Lucien-Brun 1997). In China, shrimp farming is an important industry in the coastal area employing, directly and indirectly, an estimated one million people (Qingyin et al. 1997).

REASONS FOR SHRIMP AQUACULTURE ENCROACHMENT ON MANGROVES

In September 1997, the Global Aquaculture Alliance (a group formed inside the shrimp industry) sponsored a meeting of mangrove and shrimp aquaculture experts to prepare a report on facts concerning the mangrove situation and shrimp aquaculture. The participants at this meeting further discussed the basis for a Code of Practice on the siting and operation of shrimp farms in relation to coastal mangrove forests.

Siting of shrimp ponds in coastal areas is governed by many factors, including climate, elevation, water quality, soil type, land availability, infrastructure development, population pressure, culture method, and legislative aspects. Shrimp ponds have been constructed on many different types of land, including inter-tidal land (mangroves, mud flats, and salt pans) and land above the high tide mark (rice fields, agricultural and saline lands). Land use type for shrimp farm siting varies from country to country and even within a country over time, making it difficult to generalize.

A comprehensive study of land used for shrimp aquaculture in Asia was undertaken through a survey of approximately 5,000 shrimp farms in 1994 and 1995 (ADB/NACA 1997). This study was conducted in Bangladesh, Cambodia, China, India, Indonesia, Korea, Malaysia, Philippines, Sri Lanka, Taiwan, Thailand, and Vietnam. Table 3.3 summarizes results on the land type used for shrimp farm location in these countries. Approximately 37% of all the ponds were constructed in former mangrove wetlands and 90% of these ponds used extensive practices. The surface occupied by these ponds (approximately 400,000 ha) represents 5.7% of the total existing mangrove area (6,969,982 ha) in these countries. Data from the survey gave no information on the quality of mangroves in terms of species diversity or ecological value, nor how much of the mangrove land had been previously degraded before use for shrimp farming. In contrast, a greater proportion (81%) of ponds managed intensively and semi-intensively occupies non-mangrove land and land located above the high tide mark. Such land is now widely recognized as being better for shrimp pond location, although the survey data show that some intensive farms are still located on lower land. The high use of rice fields for extensive shrimp culture is due to certain types of shrimp farming systems operated in Bangladesh, India, and Vietnam, where farmers practice alternate cropping, with rice during the rainy season at low salinities and extensive shrimp farming during the dry season.

In Latin America, shrimp farms often cover several hundred hectares. It is not unusual to find that a farm begins in former mangrove area and extends onto higher land. In Ecuador, the favorite sites were originally salt pans devoid of vegetation. Once these sites were used up, the industry moved to less favorable areas including some mangrove wetlands. Many of the farms in the Guayaquil estuary are build on islands. Much of the islands are covered by shrimp ponds and encircled by a thin strip of mangrove. Many people have the mistaken idea that the island was originally covered completely by mangrove, and all except the fringe had been cut down to build the shrimp farm. Upon examination of the pond soil, it often is evident that the central part of the island had been supra-tidal land and only a small percentage of the shrimp farm area had actually been developed in mangrove wetland.

Regarding mangrove issues, environmentalists often express concern about conversion of mangroves to shrimp ponds. While mangroves have been cut to make way for ponds, and this is the most serious impact, there may be other ways in which shrimp farming impacts mangrove ecosystems. These interactions are poorly studied, but need to be considered in efforts to control adverse impacts where farms are located in or near mangrove forests. For example, when shrimp farms are constructed on supra-tidal land, it may be necessary to construct canals for intake water and effluent discharge through the mangrove, or it may be necessary to clear mangrove to build pumping stations and service docks for shrimp farms. At most, areas cleared for canals and other infrastructures would not exceed 5% of total pond area on a farm.

Construction of ponds, canals, or access roads may alter the local hydrology of the area and cause isolation of some mangrove stands from brackishwater and/or freshwater flooding. It may also result in salinity changes leading to mangrove stress. Another class of potential impacts, although not documented and realistically less serious, involves effluent discharge with risk of eutrophication, change in salinity, or pathogen spread from shrimp ponds to mangrove fauna.

EXTENT OF MANGROVE LOSS DUE TO SHRIMP AQUACULTURE

There is no doubt that shrimp farming has contributed to mangrove loss, particularly the extensive systems requiring large areas of inter-tidal land. Although blamed specifically in recent years, aquaculture is but one source of several development activities which have contributed to the huge loss of mangrove resources worldwide (Macintosh 1996). Due to the variability and general unreliability of data, particularly on the quality of mangroves, it is difficult to assign a global loss due to shrimp aquaculture, let alone to assess its ecological significance.

Globally, if it is assumed that all of the 869,470 ha of ponds (Jory 1999) were converted from mangrove land, then shrimp ponds would account for 4.8% of the present mangrove resource, representing less than 4% of the total mangrove historical resource (Boyd and Massaut 1997, Lassen 1997). Recent analyses undertaken for the World Wide Fund for Nature (Clay 1997) also concluded that "the extent of mangrove destruction worldwide resulting from shrimp farming is only a tiny fraction of the total lost to date ... globally, shrimp farming is not responsible for even a quarter (perhaps even as little as 10%) of the mangrove clearings that have taken place since 1960." There is little hope that an exact figure will ever be known and that the extent of the social and ecological significance of such loss evaluated.

The general appproach to mangrove destruction and degradation has been based on short-term exploitation for immediate economic benefit, rather than long-term, sustainable exploitation (Macintosh 1996). A lack of effective regulation of the mangrove resources in many countries has probably contributed to the continuing destruction of mangrove forests (Marte 1995). Although laws governing mangroves were passed in some countries, a combination of exemptions for small-

TABLE 3.3: ESTIMATED LAND USE TYPE FOR SHRIMP FARMING IN 12 ASIAN COUNTRIES BASED ON A SURVEY OF AROUND 5,000 FARMS CONDUCTED DURING 1995 (ADB/NACA 1997).

Land use type prior to shrimp farming	Intensive farms		Semi-intensive farms		Extensive farms	
	Area (ha)	%	Area (ha)	%	Area (ha)	%
Inter-tidal land						
Ex-mangrove	14,142	19.0	24,786	18.6	359,118	41.9
Non forested wetland	8,669	11.6	25,206	19.0	136,121	15.9
Salt pans	7,496	10.0	4,242	3.2	20,649	2.4
Other inter-tidal	6,470	8.7	14,603	11.0	195,948	22.9
Supra-tidal land						
Rice farm	22,515	30.2	19,397	14.6	122,087	14.3
Other agriculture	8,432	11.3	4,603	3.5	8,215	0.9
Non agriculture	7,397	9.9	36,278	27.3	25,601	3.0
Estimated total farm area	74,600	100	133,000	100	856,300	100

Study conducted in Bangladesh, Cambodia, China, India, Indonesia, Korea, Malaysia, Philippines, Sri Lanka, Taiwan, Thailand, and Vietnam.

scale exploitation and lack of enforcement led to the wrong impression that mangrove forests were essentially free resources (Fegan 1996). In Ecuador, the penalties for cutting mangrove trees at present are sufficiently low that it can often be cheaper to break the rules and pay minimal fines than to bother with compliance (Barnhizer 1997). During the 1997 Shrimp Tribunal Session, both the Ecuadorian government and the shrimp industry representatives acknowledged the need for new and stronger penalties for violation of regulations governing and permitting mangrove cutting. Fortunately, there is increasing recognition of the problem and positive efforts are being taken to mitigate negative impacts caused by shrimp culture. Such efforts need to be further strengthened.

The negative environmental impacts of the decline in mangrove areas have been widely publicized and include losses of the various uses, functions, and attributes mentioned in the previous chapter. It is also important to recognize that shrimp aquaculture has both contributed to and been affected by the mangrove degradation. Environmental damage impacts negatively on aquaculture through water pollution, potential loss of post-larval resources, and lack of protection against storm surges. Such ecological changes can also have serious social and economic impacts, particularly on coastal inhabitants who are dependent on mangrove resources for livelihood and food. These changes may be especially serious when there are limited opportunities for alternative employment and sources of food production in coastal areas, or when changes in land use in mangrove areas lead to coastal people being denied access to areas which they have used for their livelihoods for generations (Bailey 1988).

IV TECHNIQUES FOR MANGROVE REFORESTATION AND MANAGEMENT[1]

INTRODUCTION

FOR UNIFORMITY in the vocabulary, the words *propagule* and *seedling* will be used as defined by Lewis (1982). The word *propagule* will refer to the seeds or seedlings of a species that are collected directly from the tree, or very soon thereafter, and have not exhibited any additional expansion or root formation. This is preferable to using *seed* or *seedling* because these words are often used interchangeably for the same thing, depending on the writer's determination as to how viviparous a particular species is considered (Lewis 1982). The term *seedling* will apply to propagules that have germinated and show additional changes such as the loss of the testa in *Avicennia* or root growth from the radicle in *Rhizophora*.

It is now well established that mangrove wetlands play significant roles in the coastal ecosystem whether physical, ecological, or socio-economic. The recognition of this importance is discernible from the various measures currently directed toward the sustenance of the mangrove resources such as issuance of relevant regulations, enhancement of conservation programs, and restoration of degraded forest (Soemodihardjo et al. 1996). Restoration can be defined as the act of bringing a particular ecosystem back to use or as nearly as possible to its original condition (Field 1996). In the context of mangrove forests, restoration will seldom mean returning the ecosystem to its original condition, but will more often mean bringing it back to a state of effectiveness, either for ecological or socio-economic purposes. The creation of a self-sustaining and productive ecosystem, where none existed before, must be considered as a successful outcome of any mangrove restoration process (Lugo 1988).

Mangrove restoration is a much younger technology than upland reforestation, especially in temperate zones, and has received far less attention, funding, and research efforts (Thorhaug 1988). In the introduction to his mangrove restoration manual, Field (1996) refers to J.G. Watson as the pioneer in commercial mangrove plantations and reports that the approach he took 70 years ago remains essentially the same today, despite the enormous amount of research on the biology

[1] *This chapter is based heavily on a recent publication on techniques for mangrove reforestation by the International Society for Mangrove Ecosystems: Restoration of Mangrove Ecosystems, C. Field (ed.), 1996. The manual contains detailed information on mangrove restoration techniques and presents case-studies from 13 countries to illustrate the variety of problems and solutions encountered during restoration programs.*

and ecology of mangroves. Watson made the following comments: "Where seed-bearers of the Rhizophora are wanting, it may be necessary to collect germinating (propagules) from trees nearby, and stick them in the mud...care should be taken to select those healthy (propagules) for the purpose, and to use only those that have recently fallen from the trees or that will come away without pulling...the (propagules) should be stuck into a depth of a few inches only, so that they will not fall over; deep insertion is not recommended...the (propagules) are thrust into the mud at intervals of 40 to 100 centimeters...young plantations are protected from damage by floating objects" (Field 1996).

The approach adopted to restoration will depend on the local conditions and the rationale for restoration (Field 1996, R. Lewis, Lewis Environmental Services, Inc., Tampa, Florida, USA, personal communication). It is, therefore, very difficult to generalize on the techniques that should be adopted for the restoration of a mangrove ecosystem at a particular site (Soemodihardjo et al. 1996). However, there are some general principles that should be followed when contemplating the restoration of a particular mangrove site.

- The objective of the restoration program must be clearly defined before any project is undertaken, as this will largely define the chosen approach (Field 1996).
- It is critical to have a clear understanding of the nature and dynamics of locally occurring mangrove ecosystems, as this will be the best guide to any restoration program (Lewis 1982, Field 1996, Soemodihardjo et al. 1996).
- Investigation on the local hydrology should guarantee that it is adequate to support the mangrove species of choice. As a rule of thumb, if there is no natural colonization on the site, the hydrology is not adequate and direct planting with no attempt to restore good tidal flooding conditions will fail (R. Lewis, Lewis Environmental Services, Inc., Tampa, Florida, USA, personal communication).
- The planting techniques themselves, once established, are not difficult. However, the overall design, including choice or preparation of planting site, choice of species, planting method, and anchoring systems, is still only well executed by experts in restoration of mangroves (Thorhaug 1988).

Mangrove restoration programs have been started for a wide variety of reasons including: protection of coastal areas, stabilizing land and reducing erosion, creation of habitats for terrestrial animals, providing nursery and breeding grounds for aquatic resources, supplying part of the demand for firewood and poles, reducing the pollution caused by agricultural and industrial wastes, creation of employment, improving the standard of living for rural inhabitants through silviculture and aquaculture, and injecting resources into national economy. The primary objectives of mangrove reforestation can be summarized into two categories: (1) to restore the ecological function of degraded mangrove land, and (2) to obtain forest products that are of commercial value. In a general context, commercial value means forest products that meet the needs of coastal villagers for sources of energy and housing material, as well as the needs of industry for raw material (Soemodihardjo et al. 1996). The general guidelines to be given here pertain more to the restoration of a natural mangrove ecosystem on an impaired site, where mangroves have been disturbed or degraded by human activities or natural causes, than to the maintenance of a commercial mangrove forest, although there are similarities in the approach. Foresters interested in the production of commercial quantities or timber and charcoal from the mangrove forest use clear-felling and replanting techniques that will achieve uniform stands of trees. These approaches have their advantages and disadvantages and concentrate on the production of forests for commercial exploitation only, with little attempt to restore full ecological value (Field 1996).

Two approaches can be used in the restoration of degraded or reclaimed mangrove areas: natural regeneration or artificial regeneration (Field 1996). Natural regeneration depends solely on naturally occurring propagules as the source for seedlings, and the mix of species regenerated will be dependent on the species left in the restoration area. The main advantage of natural regeneration is that the resulting forest is likely to be more akin to the original mangrove vegetation, unless there have been severe changes in the damaged forest (Field 1996). Other advantages of this method are that it is cheap to establish, requires less labor, and results in less soil disturbance (Field 1996). However, it is dependent on the number of seed-bearing trees left on the site, and because it is not attended, propagule establishment will depend on the extent of pests occurring at the site. Artificial regeneration is the primary method of reforestation discussed in this chapter. This method involves planting propagules or seedlings in areas where there is insufficient natural regeneration (Field 1996). The advantages of artificial regeneration include control of species composition and distribution, introduction of genetically improved stock, better control of pests, and restoration of sites presenting non-optimal conditions.

SELECTION AND PREPARATION OF REFORESTATION SITE

SITE SELECTION. The planting of mangroves cannot be done in every blank spot or empty mudflat and a careful evaluation of potential sites is a critical element in restoration programs (Qureshi 1996). Optimal characteristics of a site will vary greatly with local conditions and the mangrove species to be planted (Field 1996, Saenger 1996). A number of physico-chemical factors at the planting site should be considered because of their role as primary determinants in mangrove growth and development. They should include temperature, insolation, stability of the site, exposure to wind and coastal currents, rate of siltation, evaporation, nature of the soil, height of the water table, tidal conditions, proximity of freshwater source, salinity of the soil water, presence of pests, signs of natural regeneration, and availability of propagules (Field 1996, Padron 1996, Qureshi 1996, Saenger 1996).

Some general criteria in the selection of a mangrove restoration site are listed below:

- The best sites for planting lie between the mean sea level and the mean high water level (Qureshi 1996, Siddiqi and Khan 1996). Young seedlings should be inundated regularly by the tide (Field 1996). The optimal degree of inundation needed will depend on the mangrove species to be planted. Generally, the Rhizophoraceae can be planted in zones of longer inundation than species that are usually found in the upper tidal zone such as *Avicennia* and *Laguncularia* (Lewis 1982, Field 1996).
- Mangroves thrive best on slightly sloping ground, which drains tidal water back into creeks, rather than flat ground where the water remains and stagnates (Field 1996, Qureshi 1996).
- The presence of seagrass, naturally occurring seedlings, or scattered growth of salt-tolerant grasses indicates that the site may be fit for mangrove reforestation (Field 1996).
- The soil must be structurally stable, whether it is sandy, muddy, or clayey (Field 1996, Qureshi 1996). However, the planting of mangroves can stabilize loose soils and make them firmer.
- The planting site needs to be sheltered and erosion at the site minimal (Field 1996). Strong winds and tidal currents can seriously affect the survival and growth of mangrove seedlings.
- Heavy emphasis on planting an area with a species that will naturally flood the site with propagules and regenerate quickly and naturally is obviously a waste of money (Lewis 1982).

Because of high population densities, urban spread, and traditional uses of mangrove resources, there is often a lack of suitable natural habitat for restoration (Lewis 1982, Snedaker and Biber 1996). In Thailand, the Forestry Department has difficulties in identifying potential sites for reforestation because of a regulation that grants property right to any person tending, cultivating, or occupying a piece of public land. They have to experiment on new techniques for restoring suboptimal sites such as extending mudflats. In Florida, USA, when no suitable site can be identified, coastal upland areas are often chosen. These sites need to be scraped to lower elevations to permit tidal flooding and the planting of mangroves (Snedaker and Biber 1996). Restoration of such sites will obviously increase the cost of the operation.

A final consideration, but one that is essential for nearly all restoration projects, is the level of cooperation from the local communities (Lewis 1982, Field 1996). If the local communities are persuaded that the restoration project will benefit their lifestyle and environment, then they are more likely to ensure that the restoration effort is a success. Cooperation may involve supplying labor during site preparation or collection of plant material, limiting damage to the site by preventing grazing or collection of firewood, and protecting the site from illegal activities (Field 1996).

SELECTION OF MANGROVE SPECIES. The successful growth of any particular species of mangroves depends largely on its tolerance to certain environmental factors (Saenger 1996, Siddiqi and Khan 1996). As a consequence, to maintain a mangrove community, data are required on the environmental characteristics of the site and on the intrinsic attributes of the plants being considered for the site (Saenger 1996). Field (1996) recommends that the selection of mangrove species to be planted should be based on the following three factors in decreasing order of importance:

- The mangrove species occurring naturally in the locality of the restoration site.
- The availability of propagules.
- The objective of the restoration program.

For example, Aksornkoae (1996) recommended the planting of *Rhizophora apiculata* on a site fringing the coastline in Thailand, if the restoration site needed to serve as a source of wood for charcoal, increased fishing opportunities for mangrove dwellers, and protected the coast from storms and soil erosion. This particular mangrove species already occurred at the highest density in the local mangrove forests. Its root system has a capacity to resist erosion and withstand wave actions, both factors being characteristic of the chosen restoration site. It also produces dense hardwood and good quality charcoal with high calorific value and little smoke (Aksornkoae 1996). In another case-study, Snedaker and Biber (1996) recommended *Rhizophora mangle* over the three other mangrove species occurring naturally in Florida as the preferred species in restoration

TABLE 4.1: ZONATION OF MANGROVES IN THE PHILIPPINES (FROM FIELD 1996).

Zone	Tidal inundation regime	Soil types	Common mangrove species occurring naturally
Seaward	Daily, including neap tides	Coral rubble, sandy, sandy loam	*Avicennia marina, Rhizophora apiculata, Rhizophora stylosa, Sonneratia alba, Sonneratia caseolaris*
Middle	Daily, except during neap tides	Silty to silty clay	*Aegiceras corniculatum, Aegiceras floridum, Avicennia alba, Avicennia officinalis, Bruguiera cylindrica, Bruguiera gymnorrhiza, Bruguiera parviflora, Bruguiera sexangula, Ceriops decandra, Ceriops tagal, Excoecaria agallocha, Lumnitzera racemosa, R. apiculata, Rhizophora mucronata, Xylocarpus mekongensis*
Landward	Inundated only during spring tides	Silty to silty-clay to clay	*A. alba, B. sexangula, C. tagal, E. agallocha, Heritiera littoralis, Nypa fruticans, Scyphiphora hydrophyllacea, Xylocarpus granatum, X. mekongensis*
Riverine	Variable inundation brackish/ freshwater influence	Sandy to silty clay	River mouth: *A. corniculatum, A. floridum, A. marina, A. officinalis, Camptostemon philippinensis, R. apiculata, R. mucronata, R. stylosa* Upstream forebank and backbank: *A. corniculatum, A. floridum, A. alba, A. officinalis, B. cylindrica, B. gymnorrhiza, B. parviflora, C. philippinensis, E. agallocha, H littoralis, N. fruticans, R. apiculata, R. mucronata, X. granatum, X. mekongensis*

projects in this region, because of its higher survival potential over a wide range of conditions.

The zone in which the mangroves should be planted, such as seaward, middle, landward, or riverine upstream or downstream, can be determined by observation of the mangrove species occurring naturally (Lewis 1982, Field 1996, Saenger 1996). Table 4.1 gives a summary of the observation on the zonation of mangroves in the Philippines and provides a helpful model of the type of information that is required before deciding on mangrove planting.

Field (1996) gives a list of mangrove species that have been successfully planted around the world, with an indication of the aims of the restoration program (Table 4.2). It is noteworthy that the number of species that have been planted represents only a very small proportion of the total number of mangrove species that are known to exist (i.e., around 31%; refer to Appendix 1 for comparison).

PROPAGULES COLLECTION AND TRANSPORTATION. Freshly fallen propagules or ripe propagules which are easily detached from the parent tree can be used in restoration programs (Fig. 4.1; Thorhaug 1988, Field 1996, Qureshi 1996, Saenger 1996, Siddiqi and Khan 1996). It is important that the fruiting times for the mangrove species to be planted are carefully observed to ensure propagule availability and optimum time for collection (Lewis 1982, Field 1996). If propagules are collected from a tree when they are too young, they will not be able to take root or may die some weeks after being planted (Field 1996, Hong 1996, Untawale 1996). Maturation of propagules will depend on the season, the location, and the species of choice. For example, a length/weight ratio of 1.40 to 1.55 is an indication that propagules of *Rhizophora mangle* are ripe (Bohorquez 1996). However, the ripe index is seldom used and propagule collectors rely on external characteristics of the fruit to decide on its ripeness. Table 4.3 lists the characteristics of ripe propagules for a variety of common mangrove species.

After collection, propagules should be sorted and checked for evidence of disease, deformities, or damages (Thorhaug 1988, Snedaker and Biber 1996). Small, non-uniformly colored, broken, or bruised propagules should be discarded (Aksornkoae 1996, Field 1996, Hong 1996, Padron 1996). Mature propagules showing signs of attack by borer insects should not be included in the reforestation effort (Lewis 1982, Field 1996, Padron 1996). If propagules are collected from the mangrove forest floor or the water surface, the chances of insect attack and fungal disease are greater (Field 1996, Hong 1996).

If propagules have to be transported over significant distances, care must be taken to preserve their viability (Field 1996). Most often, the large propagules of Rhizophoraceae species must be kept moist (but not wet) and protected from overheating (Hong 1996, Saenger 1996). It is recommended that they are placed in damp, jute bags or stored in baskets made of bamboo or banana leaves (Field 1996). However, this damp environment will also encourage insect and fungal attack. The viability of the propagules after collection declines quite fast; in an experiment in Bangladesh (Siddiqi and Khan 1996) no seed was found to germinate when sown 60 days after collection.

TABLE 4.2: THE MAIN SPECIES OF MANGROVE PLANTED IN COUNTRIES AROUND THE WORLD (FROM FIELD 1996).

Country	Main Mangrove Species Planted	Aim(s) of planting program
Australia	*Aegiceras corniculatum, Avicennia marina*	Enhancement of natural regeneration
Bangladesh	*Avicennia officinalis, Heritiera fomes, Sonneratia apetala*	Sustained yield of forest products; coastal protection
Benin	*Rhizophora mangle, Rhizophora racemosa*	Restoration of degraded areas; introduction in new locations
China	*Kandelia candel*	Coastal protection
Colombia	*R. mangle*	Restoration of a national park
Costa Rica	*Rhizophora harrisonii, R. mangle*	Timber production
Cuba	*Avicennia germinans, Conocarpus erectus, Laguncularia racemosa, R. mangle*	Barriers to erosion; restoration of degraded areas; timber
India	*A. marina, A. officinalis, Rhizophora apiculata, Rhizophora mucronata, Sonneratia caseolaris*	Restoration of degraded areas
Indonesia	*Bruguiera gymnorrhiza, R. apiculata, R. mucronata, Rhizophora stylosa*	Restoration of degraded areas
Malaysia	*R. apiculata, R. mucronata*	Timber and charcoal production
Myanmar	*A. officinalis, B. gymnorrhiza, Ceriops decandra, K. candel, R. apiculata, R. mucronata, S. apetala*	Restoration of degraded areas; timber production; firewood production
Pakistan	*A. corniculatum, A. marina, Ceriops tagal, R. apiculata, R. mucronata*	Restoration of degraded areas; timber production
Panama	*R. mangle*	Restoration after an oil spill
Philippines	*C. tagal, Nypa fruticans, R. apiculata, R. mucronata, R. stylosa*	Restoration of degraded areas
Sierra Leone	*R. mangle, R. racemosa*	Restoration of degraded areas
Sri Lanka	*R. apiculata, R. mucronata*	Protection of lagoons and estuaries
Thailand	*R. apiculata, R. mucronata*	Timber and charcoal production
USA	*A. germinans, C. erectus, L. racemosa, R. mangle*	Restoration of natural areas
Vietnam	*Avicennia alba, C. decandra, K. candel, N. fruticans, R. apiculata, R. mucronata, R. stylosa, S. caseolaris*	Restoration of degraded areas; sea dike protection; mixed shrimp farming-mangrove areas

Storage for more than 20 days is not recommended (Snedaker and Biber 1996).

PREPARATION OF REFORESTATION SITE. Once the site and the species to be planted have been identified, a site inspection should be made to get a general picture of the environmental setting and the physical condition of the area (Soemodihardjo et al. 1996). In the case of large areas to be planted, a working map showing localities needing full planting and those needing only enrichment planting can be produced. The site should also be divided by working trails (Fig. 4.2)into smaller compartments, so that the large area is manageable and easily accessed by planters (Chan 1996, Duke 1996, Field 1996). Such trails could later be used for monitoring and maintenance activities of the plantation (Soemodihardjo et al. 1996). Preparation of the site will depend on the environmental conditions present at the site, the species, and the reforestation methods to be employed (Padron 1996). In most of the case studies reviewed, very little preparation of the planting site was considered necessary (Field 1996).

Figure 4.1. Propagules of *Rhizophora* still attached to the mother tree.

Figure 4.2. Working trail for a restoration site, cutting through a mangrove wetland, Cartagena, Colombia.

Before planting, the site must be cleared of all debris such as coconut or banana trunks, bamboo, tree branches, and undergrowth (Duke 1996, Field 1996, Soemodihardjo et al. 1996). Debris left on the site will float and shift back and forth with tides and water currents, and it can destroy newly planted seedlings (Soemodihardjo et al. 1996). Clearing of plant debris by burning should be avoided if natural regeneration is occurring on the site. At some sites near the coastline that are temporarily flooded, coastal

TABLE 4.3: CHARACTERISTICS OF RIPE PROPAGULES (ADAPTED FROM FIELD 1996).

Mangrove species	Condition for collection
Aegiceras corniculatum	Fruits become lightly pink to brown on maturation
Avicennia spp.	Seed coat changes from green to light yellow - seed coat becomes wrinkly
Bruguiera spp.	No abscission collar - hypocotyl changes color from green to brown
Ceriops decandra	Yellow abscission collar
Conocarpus erectus	Seed capsule becomes dry and cracked - color changes from pale green to brown
Heritiera fomes	Mature fruit is dark brown in color
Kandelia candel	Mature propagules display a reddish hue and fall easily - reddish abscission collar
Laguncularia racemosa	Green fruits become tinged with red and brown
Nypa fruticans	Seeds change color from light brown to dark brown upon maturation
Rhizophora spp.	Ring-like mark (red to yellow in color depending on the species considered) on the hypocotyl adjacent to the pericarp with swollen basal portion of pericarp
Sonneratia spp.	Fruit changes color from light green to dark green with maturation
Xylocarpus granatum	Fruit changes color from light brown to dark brown upon maturation

grass such as *Spartina* spp. may grow and should be left on the site because they will protect newly established propagules from being washed out, and from direct sunshine and desiccation (Padron 1996, Snedaker and Biber 1996).

Planting sites on dry marginal land, such as abandoned paddy fields, may be covered by the mangrove fern, *Acrostichum* spp. (Chan 1996, Field 1996, Soemodihardjo et al. 1996). The fern can smother propagules and seedlings. *Acrostichum* spp. is difficult to eradicate and it may only be possible to clear patches around the individual seedlings (Chan 1996, Field 1996). The fronds may be cleared manually. They can be cut with machetes (Soemodihardjo et al. 1996) or uprooted with a wedged iron bar. However, manual methods are not always effective and are laborious (Chan 1996). The herbicide Hexazinone (trade name Velpar 90) has been found effective in the eradication of the mangrove fern and is employed in different countries in Asia (Chan 1996, Field 1996, Soemodihardjo et al. 1996). However, its potential negative effects on the aquatic environment are not known. For this reason, Chan (1996) recommends that the herbicide use be confined to inland areas where tidal inundation is infrequent.

NURSERY TECHNIQUES FOR SEEDLING

ADVANTAGES OF NURSERY GROWN SEEDLINGS. The type of plant material to use–either propagules, seedlings, or transplants collected from the wild for direct planting, or seedlings or trees grown in nurseries–will depend on the primary objective of the restoration effort (Saenger 1996). Costs, expected success, and time lapse until the planting is mature must be balanced (Lewis 1982). For example, if the primary objective of the reforestation effort is to stabilize riverbanks, larger specimens exhibiting good development of their root systems are recommended (Saenger 1996). In sites with harsh environmental conditions, nursery grown seedlings show higher success rates (i.e., greater survival and growth) than direct planting of propagules (Thorhaug 1988, Saenger 1996).

Nurseries normally are formed when regeneration by direct planting of propagules is anticipated to be difficult or when it is necessary to produce seedlings of a required size before planting (Field 1996). Nurseries are particularly useful for mangrove species, such as *Aegiceras*, *Avicennia*, or *Sonneratia*, which have relatively small seeds that are easily washed away when directly sown (Fig. 4.3; Field 1996, Qureshi 1996). They can also be beneficial if they provide young plants that are more resistant to pests (Thorhaug 1988, Soemodihardjo et al. 1996). For any large scale restoration program, nurseries are essential because they prevent the risk of not finding enough suitable propagules in nearby natural forests and will ensure a regular supply of seedlings of different mangrove species (Saenger 1996, Untawale 1996). In addition, growing seedlings in nurseries is relatively simple (Saenger 1996).

These various advantages mentioned above make nursery grown seedlings an extremely useful source for replanting programs. However, higher nursery costs and increased difficul-

Figure 4.3. Seed trial in a nursery, Ranong, Thailand.

ties in planting when compared to propagules, may offset the advantages in certain situations (Thorhaug 1988, Saenger 1996).

NURSERY SITE SELECTION. The first thing to do when preparing mangrove nurseries is to select an appropriate site (Soemodihardjo et al. 1996). One of the most important criteria in the nursery site selection is that the site should be as close as possible to the restoration area (Field 1996). It should also be flat and located on a proper muddy soil (Soemodihardjo et al. 1996). The position of the nursery site compared with the tidal inundation level will depend on the type of mangrove species reared and its particular requirement, but often it is recommended that the site be flooded by the tide daily (Field 1996, Qureshi 1996, Saenger 1996). Control of tidal water can be achieved by building a small embankment around the site. At the early stages of propagule development, nursery beds are shaded to reduce stress by direct sunlight, such as desiccation (Fig. 4.4). For this purpose, leaves of the palm tree, *Nypa fruticans*, or from the mangrove fern, *Acrostichum*, can be used (Soemodihardjo et al. 1996). Pests tend to be a problem in the dense, monoculture situation encountered in nurseries (Snedaker and Biber 1996). The site location should favor maximum control on potential pests, such as crabs and monkeys.

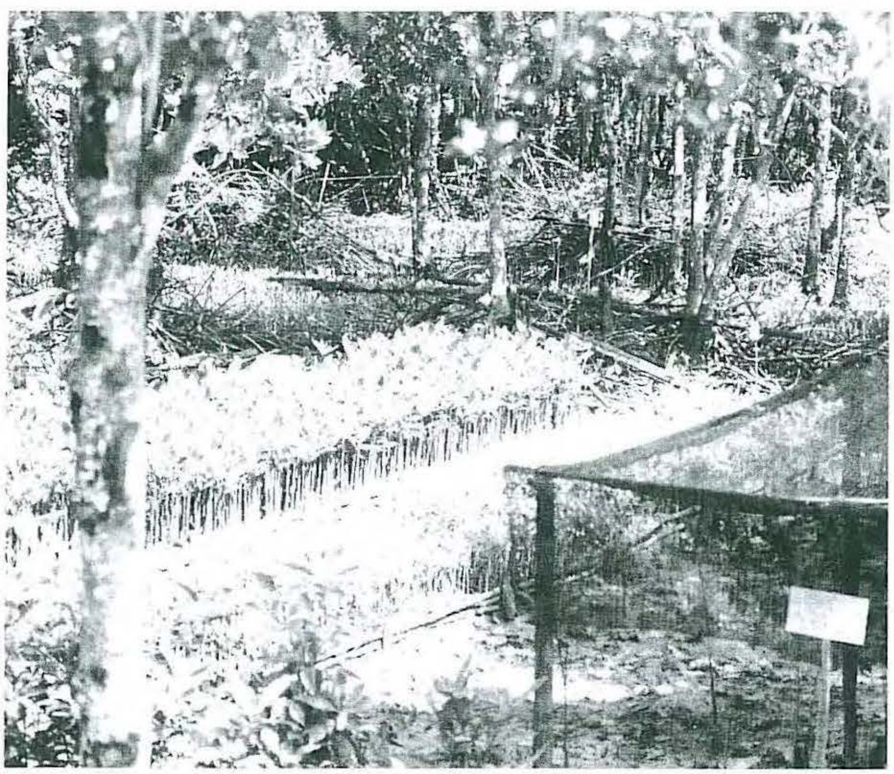


Figure 4.4. Nursery located in the inter-tidal zone, Ranong, Thailand.

NURSERY TECHNIQUES. As already mentioned, growing seedlings in nurseries is relatively simple (Saenger 1996). Propagules are buried in a vertical position to about one-third of their total length directly in planting beds with freely draining, good quality mangrove soil. Planting beds can be elevated or not, and are often 1.2 m x 1.2 m. The beds are separated by 30 cm wide and 20 cm deep channels to facilitate water drainage (Field 1996). The seedlings are left to grow under ambient weather conditions, but they should be watered daily, either by the tide or nursery attendants (Qureshi 1996, Soemodihardjo et al. 1996). Brackish or sea water is preferable, because it helps in suppressing fungal infections and acclimates the seedlings to the saline conditions into which they are to be transplanted (Hong 1996, Saenger 1996, Snedaker and Biber 1996). Sometimes the propagules are transplanted in plastic bags (15 cm height x 10 cm diameter or 15 cm x 25 cm) and mangrove soil is replaced with potting mixture of fresh soil and sand. Holes are made in the bags so that water can drain easily (Hong 1996). The nursery beds are the same size as that used for direct burying but in this case the plastic bags are placed side by side in the bed. This technique will facilitate transportation of the newly developed seedlings from the nursery to the planting site. However, there are some indications that plastic bags in nurseries could inhibit root growth (Field 1996).

In some commercial nurseries, seedlings are fertilized on average every 3 to 6 months once they have become established in tree cones or small pots (Field 1996). The specific fertilizers that are used vary among nurseries, some using palm and citrus tree fertilizer products (N:P:K = 7:2:7), others using garden fertilizer (N:P:K: = 5:8:5) (Snedaker and Biber 1996). Such nurseries will transfer seedlings to larger pots generally every 12 months, or when the root-ball exceeds the size of the pot (Snedaker and Biber 1996).

Survival of plants at the nursery stage is usually reported to be as high as 70 to 100% for all species (Field 1996). Regular control of weeds and insect pests is required (Field 1996). On average, seedlings are ready for transplanting after 3 to 6 months, at which time they normally have developed three pairs of leaves (Aksornkoae 1996, Soemodihardjo et al. 1996). A summary of the results of a wide ranging nursery trial in Bangladesh is given in Table 4.4.

TABLE 4.4: MATERIAL USED, WEIGHT OF SEEDS, VIABILITY, GERMINATION SUCCESS, AND SEEDLING GROWTH OF 17 MANGROVE SPECIES IN BANGLADESH (FROM FIELD 1996).

Name of species	Materials collected	Average number of seeds/fruit	Average number of seeds/kg	Sowing materials	Germination period (days)		Germination success (%)	Storage time with watering (days)	Seedling height after 10 months (cm)
					Initiation	Completion			
Aegiceras corniculatum	Fruit	1	800-1,000	Fruit	20	50	100	30	30-40
Avicennia alba	Fruit	1	300	Fruit	3	10	90	15	50-80
Avicennia marina	Fruit	1	300	Fruit	3	10	90	15	60-80
Avicennia officinalis	Fruit	1	300	Fruit	3	10	90	15	70-90
Bruguiera sexangula	Propagule	1	70-80	Propagule	10	40	100	30	25-30
Ceriops decandra	Propagule	1	150-200	Propagule	10	40	95	30	25-30
Cynometra ramiflora	Fruit/Pod	1	160	Pod	7	60	80	60	35-45
Excoeccaria agallocha	Seed	2-3	4,000	Seed	5	21	75	30	40-70
Heritiera fomes	Fruit	1	75-80	Fruit	8	48	85	40	50-60
Lumnitzera	Fruit	1	9,000	Fruit	7	60	20	15	20-30
Nypa fruticans	Fruit	1	10-12	Fruit	7	30	95	60	80-90
Phoenix paludosa	Fruit	1	12,000-15,000	Seed	70	150	80	60	40-50
Rhizophora mucronata	Propagule	1	12-15	Propagule	7	20	100	30	100-125
Sonneratia apetala	Fruit	50	22,000	Seed	4	7	75	30	80-100
Sonneratia caseolaris	Fruit	2,000	35,000	Seed	4	7	60	30	70-90
Xylocarpus granatum	Fruit	5-15	5-8	Seed	20	90	60-65	60	80-120
Xylocarpus mekongensis	Seed	8-10	100-125	Seed	14	80	70	90	70-90

MANGROVE TRANSPLANTATION

TRANSPLANTATION METHODS. In the early days of mangrove reforestation, propagules were simply broadcast on mangrove forest floors (Untawale 1996). The survival rate was quite poor and the majority of the propagules were washed away by tidal currents before having a chance to root (Snedaker and Biber 1996). This method is currently used only at sites covered by salt-tolerant grasses that can serve as anchors for the propagules, with a success rate for germination of 40-60% (Qureshi 1996, Snedaker and Biber 1996). The three main transplantation methods used in reforestation programs are as follows: direct burying of collected propagules; transplanting nursery-grown seedlings; or transplanting small mangrove trees, either collected from the wild or grown in a nursery. The last two methods are effective techniques in overcoming problems related to predation and are often recommended for problematic sites. Under most circumstances to date, the decision on what type of plant material to use has led to the use of propagules or seedlings because of their ready availability, low cost, and ease of installation (Lewis 1982).

Direct burying of propagules involves inserting ripe propagules by their rooting end into the often soft and moist mud (Qureshi 1996). The depth of planting is usually one quarter to one third of the propagule length (Fig. 4.5; Field 1996, Hong 1996). If the propagule is buried too deep, mud will block the lenticels, the hypocotyl cannot respire, roots do not form, and the propagule dies (Snedaker and Biber 1996). If the

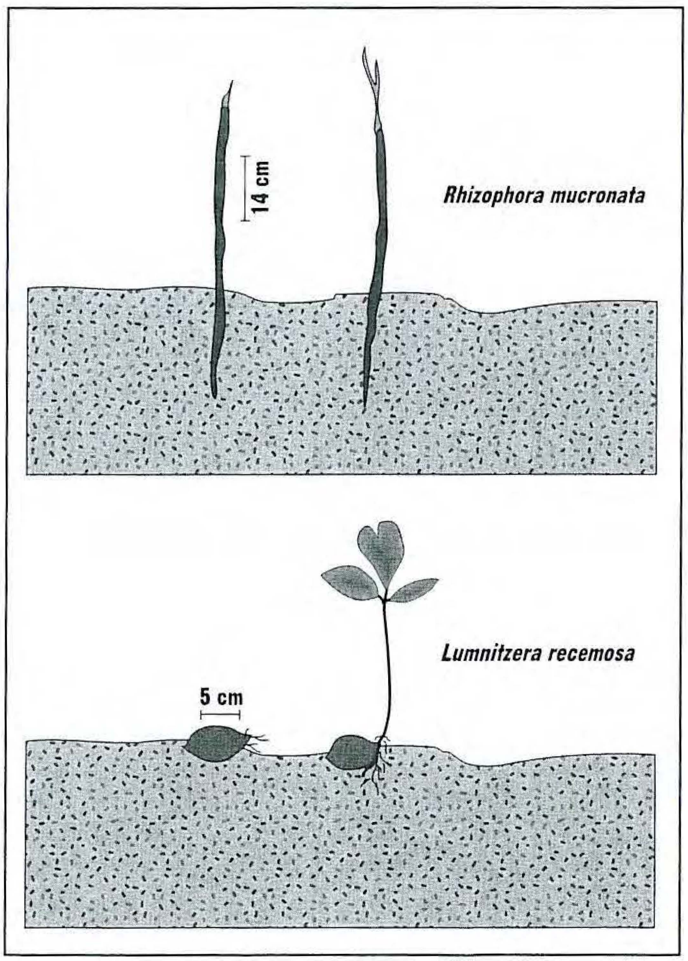


Figure 4.5. Sketch of propagules buried in soil.

Figure 4.6. Newly planted seedling of *Rhizophora mangle* stabilized with branches.

propagule is inserted too shallow, it will be easily washed away by the waves and tides (Hong 1996). The planting of propagules should be done at a time when the area is not expected to be flooded for at least a week or so, thereby allowing them to be firmly established prior to inundation (Saenger 1996, Snedaker and Biber 1996). On rather hard or sandy soil, holes should be dug deep enough with a stick for the propagules to be held firmly (Field 1996, Soemodihardjo et al. 1996). Losses are expected and re-seeding is frequently necessary (Snedaker and Biber 1996). If losses are high, propagules may need to be held in place temporarily using chicken wire or seagrass matting (Fig. 4.6; Saenger 1996).

Use of seedlings ensures better survival and establishment rates and more rapid growth, in comparison with direct burying of propagules (Snedaker and Biber 1996). Transplanting of nursery grown seedlings is carried out by creating planting holes and embedding the plug of soil carrying the seedling (Untawale 1996). If the seedling was grown in a plastic bag at the nursery, the bag should be removed prior to planting (Field 1996, Soemodihardjo et al. 1996).

Young trees or wildings can be collected from natural mangrove areas by extracting them with a specially designed steel corer to avoid damaging the root system (Chan 1996). If roots are broken during this process, salt water will be absorbed into the stem and leaves and some months later the plant will die (Hong 1996). Young trees can be planted with the root-ball still attached or soil-free. The first method is recommended because it will yield higher survival rate and prevent the root system from drying out or from overheating (Bohorquez 1996, Snedaker and Biber 1996). Root-ball transplants can be held in containers only for a limited period prior to planting while survival is generally inversely proportional to their size and the length of time held in containers (Saenger 1996). Planting consists of placing the transplant in a prepared hole at a similar tidal level as the original habitat. Inclusion of a slow release fertilizer (N:P:K = 18:2.6:10) during planting appeared to assist in the recovery period (Saenger 1996). Twig and branch pruning during transplanting apparently enhances recovery, and pruning up to two thirds of the original height has

Figure 4.7. Permanently opened entrance gate to an abandoned shrimp pond to reestablish good hydrological conditions for natural mangrove regeneration.

Figure 4.8. Subsequent natural regeneration of mangrove trees in the abandoned shrimp pond (7 years after reestablishment of natural flooding pattern).

been recommended (Snedaker and Biber 1996). Anchors or stakes may be necessary to ensure the stability of the young trees in high wave-energy environments (Field 1996). This method is useful for replacing dead seedlings in nearly established plantations. It will results in quicker canopy coverage, more rapid growth, and quicker substrate stabilization (Snedaker and Biber 1996).

In the particular case of restoring former shrimp ponds and surrounding areas, the general principles presented above will pertain. However, special attention should be given to return the hydrological conditions to normal and allow tidal flows to reach the restoration area (Fig. 4.7, 4.8; R. Lewis, Lewis Environmental Services, Inc., Tampa, Florida, USA, personal communication). The majority of the present examples were conducted in abandoned shrimp ponds or in drainage canals (Fitzgerald 1997; R. Lewis, Lewis Environmental Services, Inc., Tampa, Florida, USA, personal communication).

TABLE 4.5: SPACING USED IN PLANTING MANGROVE SEEDLINGS AND PROPAGULES OF VARIOUS SIZES (FROM FIELD 1996).

Mangrove species	Spacing (m)	Seedling size
Aegiceras corniculatum	1.5 x 1.5	30-50 cm
Avicenniq marina	1.5 x 1.5	30-50 cm
Avicennia officinalis	1.0 x 1.0	70-90 cm
Bruguiera gymnorrhiza	2.0 x 2.0	propagule
Excoecaria agallocha	1.0 x 1.0	30-50 cm
Kandelia candel	0.7 x 0.7; 0.3 x 0.3	propagule
Nypa fruticans	3.0 x 3.0	80-90 cm
Rhizophora apiculata	2.0 x 2.0; 1.8 x 1.8; 1.5 x 1.5; 1.2 x 1.2; 1.0 x 1.0	propagule
Rhizophora mucronata	2.0 x 2.0; 1.8 x 1.8; 1.5 x 1.5	propagule
Rhizophora racemosa	1.5 x 1.5	propagule
Rhizophora stylosa	1.5 x 1.5; 1.0 x 1.0; 0.8 x 0.8; 0.5 x 0.5	propagule
Sonneratia apetala	1.7 x 1.7	60 cm
	1.2 x 1.2	30-60 cm

SEEDLING SPACING. Planting is generally carried out along predetermined lines and at fixed spacing by a planting crew (Chan 1996). Spacing of the seedlings is of critical importance to the economics and ultimate success of the restoration program (Snedaker and Biber 1996). In terms of cost, a decrease in the spacing by one third doubles the amount of plant material needed. A further reduction in the spacing by 50% involves nearly a ten-fold increase in the number of seedlings or propagules required. Failure to understand this has apparently caused many costly setbacks (Field 1996). The spaces between rows and between propagules change according to the local state of the land and exposure to tide and marine action (Padron 1996). Determining proper spacing should be based on the distance that will minimize early competition (Saenger 1996). Thinning will occur naturally, and by proper spacing artificial thinning can be delayed to later stages in the development of the vegetation. In general, at a mean spacing of more than one meter, self pruning does not start until the seventh year (Snedaker and Biber 1996). Table 4.5 summarizes the spacing and seedling heights that have been used in a variety of planting programs.

GROWING AND CARE AFTER PLANTING

SURVIVAL AND GROWTH MONITORING. Success is usually defined in terms of percentage survival (typically mandated at 80%) at the end of a specified period of time, usually one or two years (Snedaker and Biber 1996). Survival performances will greatly vary (from 0 to 100%) according to the technique and the type of plant material used in reforestation (Lewis 1982). Soemodihardjo et al. (1996) reported the following survival rates for a mangrove plantation in Malaysia: 85% for natural regeneration, 70% for direct planting of propagules in shaded areas, and 55% for direct planting of propagules in areas without shade. Table 4.6 illustrates varying survival rates of a mangrove plantation according to the technique used for transplanting in Sindhurg District, India (Untawale 1996).

TABLE 4.6: SURVIVAL RATE OF A MANGROVE PLANTATION IN SINDHURG DISTRICT, INDIA (FROM UNTAWALE 1996).

Species	Transplanting technique	Survival rate
Rhizophora mucronata	direct sowing	75 to 80%
	1-year-old naked seedlings	20 to 25%
	1-year-old nursery-raised seedlings in plastic bags	80 to 85%
Avicennia officinalis	broadcasting	20 to 30%
	1-year-old naked seedlings	30 to 40%
	1-year-old nursery-raised seedlings in plastic bags	80 to 90%

Results from extensive reforestation efforts in Vietnam show that the survival rate of seedlings can be very low if the right procedures are not followed (Hong 1996). Several authors have noted that the two most critical factors in successful projects are a site with little or no wave action against the shore to dislodge young plantings and proper elevation within the intertidal zone (Lewis 1982, Field 1996, Saenger 1996, Snedaker and Biber 1996). Sometimes, if proper protection is given

Figure 4.9. Monitoring of growth and biomass production in a four-year old replanted site.

to ensure good survival, the regeneration and growth of mangrove plants will be much faster (Untawale 1996). Other important factors in the success of reforestation include low damage from natural pests, selection of good propagules, intensive care by foresters, good design and execution in the project planning, appropriate funding to complete the restoration process adequately, and good participation by villagers living near the restoration areas (Aksornkoae 1996, Snedaker and Biber 1996).

There is a widespread feeling in the scientific and conservation communities, that numerical survival criteria are not sufficient in estimating success of reforestation programs. Survival rates do not take into account important ecological aspects of the mangrove ecosystem such as the presence of resident and migratory wildlife and the establishment of marine and estuarine animals (Snedaker and Biber 1996). For this reason, reports on success of reforestation should include data on survival and growth rates of individual seedlings (Fig. 4.9), on changes in density and stand development inside marked plots, and on natural re-colonization of the mangrove habitat by attached invertebrates, marine animal, and terrestrial fauna (Duke 1996, Padron 1996). Regeneration estimates could also present information as follows:

- Recovery in ground cover: Lewis (Lewis Environmental Services, Inc., Tampa, Florida, USA, personal communication) gave an example of shrimp ponds in Costa Rica that were allowed to return to mangrove forests by natural regeneration, where 60% recovery in ground cover was found after 10 years.
- Natural recruitment at the mangrove site: At the Brisbane airport reforestation site (Australia), naturally recruited seedlings of both *Avicennia* and *Aegiceras* dominated the site 6 years after the reforestation took place, indicating that a self-maintaining mangrove community had been established (Saenger 1996).
- Ecological benefits from the restoration program: Padron (1996) noticed that after reforestation of the study area in Cuba, coastline erosion ceased, salinity of nearby agricultural soils was controlled, and marine and terrestrial fauna came back.

COMMON PROBLEMS ENCOUNTERED. The various problems affecting restoration sites can be grouped under abiotic and biotic factors (Hong 1996).

The most common abiotic factor causing high mortality in replanted sites is the high degree of exposure to wind, currents, and wave action (Field 1996). Efforts to restore sites on rapidly eroding shorelines, exposed locations, or in areas with heavy boat-wake washes meet with little success (Snedaker and Biber 1996). Ideally, any planting in unprotected sites should be behind some type of a protective barrier to provide initial wave and current protection or in substratum stabilized by grass (Untawale 1996). Seedlings can also be anchored in pneumatophores of existing mangrove trees or with rocks or other objects (Padron 1996). Floating debris such as algae, seagrass wrack, or twigs and branches can become entangled with the seedlings and propagules and cause breakage of the tender shoots (Snedaker and Biber 1996). Coverage of young leaves by floating algae or sedimentation on foliage will stop the gas exchange at the leaf surface and reduce photosynthesis efficiency, leading to seedling death. Problems with marine algae will be more marked in the dry season when they are washed ashore (Hong 1996). Planting of propagules and seedlings at the wrong tidal elevation could also result in physiological stress.

Problems caused to restoration sites by biotic factors are generally common and include a wide range of organisms. Several insects and insect larvae have been reported to attack various parts of mangrove plants. Most of the time, the problems will be associated with a certain stage in the insect development or restricted to a specific season (Hong 1996). Insect pests can be classified as insect suckers on young leaves, endophytic herbivores on apical buds, and leaf or stem borers. Intensity of insect infestation is higher in a monospecific crop. Raising a mixed plantation may be a silvicultural method for controlling insect problems (Qureshi 1996). Attacks by mangrove crabs are quite common (Soemodihardjo et al. 1996). The damages are inflicted just above or below the mud surface, by crabs eating the soft tissue around the central axis of the propagules until they are completely girded or even bitten through (Chan 1996, Hong 1996). Barnacles and oysters often cling firmly to young stems or aerial roots of mangroves growing at river mouth and low laying sea front areas (Hong 1996, Untawale 1996). Their attachment to young seedlings interferes with respiration and photosynthesis, delaying

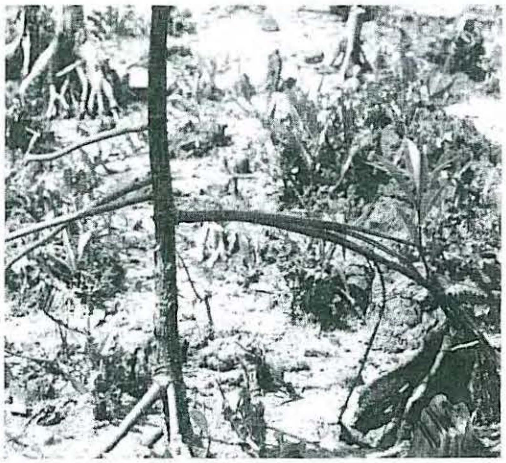


Figure 4.10. Attack by macaques on the roots of this newly transplanted seedling.

the seedling growth. It is common to find troops of long tailed macaques (*Macaca fascicularis*) gathering in newly planted areas at low tide searching for crabs and molluscs (Hong 1996, Soemodihardjo et al. 1996). Macaques will damage newly planted propagules by snapping or shearing them to devour the spongy inner tissues (Fig. 4.10; Chan 1996). In more inland areas which are less frequently inundated, *Acrostichum* ferns can grow in dense thickets and compete with seedlings for living space and light (Chan 1996, Hong 1996). A summary of pests found in mangrove plantations with potential treatment is given in Table 4.7.

Damage to transplanted seedlings by the direct or indirect influence of man has also been reported as a factor for failure of some projects (Snedaker and Biber 1997). In restoration sites close to habitations, it may be necessary to prevent unwanted grazing by cattle and other domestic animals. They trample on the planted seedlings and eat the foliage (Hong 1996). By gathering edible molluscs and fish in areas close to the restoration site, villagers may break and damage young seedlings when passing through with their boats (Untawale 1996). In Thailand, fishermen using the "push-net" method for fishing along the coast will destroy any recently established mangrove seedlings (S. Aksornkoae, Faculty of Forestry, Kasetsart University, Bangkok, Thailand, personal communication). It may also be necessary to ensure that the land is not used illegally by the local inhabitants for purposes alien to the restoration of the mangroves (Snedaker and Biber 1996).

PROBLEMS OF REMEDIATION. The main solution to problems caused by abiotic factors is to choose a good site for the restoration program. However, it is sometimes necessary to restore sub-optimal sites. This effort requires more thorough planning and has higher costs than restoration of a good site. If the area is subject to wave action and erosion, protection by barriers that maintain a normal tidal inundation and drainage should be installed during the first year (Bohorquez 1996, Qureshi 1996). Rock is the preferred barrier, but log or sandbag barriers also will attenuate wave action (Snedaker and Biber 1996). In areas with potential erodible sediments, planting halophytic grasses prior to mangrove seedlings helps to stabilize the sediment and promote suitable physical and chemical sediment qualities (Snedaker and Biber 1996). All buoyant or movable debris should be removed from the reforestation site to prevent damage to new seedlings by tidal activity or wind (Qureshi

TABLE 4.7: SUMMARY OF PESTS THAT HAVE BEEN FOUND IN MANGROVE PLANTATIONS (ADAPTED FROM FIELD 1996).

Mangrove family or species	Vulnerable part	Pest	Treatment
General	Seedling	- Soil dwelling organism, such as annelids	- Prevent build-up of excessive amounts of organic matter around seedlings
		- Competition with *Acrostichum*	- Mechanical or chemical removal of the fern
		- Excessive growth of seaweed	- Physical removal
Rhizophora spp.	Propagule	- Seed borer of the Coleoptera family	- Air dry propagules 7-14 days before planting
		- Crabs, *Sesama* spp. and *Uca* spp.	- Shield propagule with bamboo tube
		- Barnacles	- Avoid areas with barnacles
		- Monkey, *Macaca fascicularis*	- Physical protection of propagules
	Leaf	- Scale insects	- Destroy infected seedlings
		- Leaf sucker, *Monolepta orientalis*	- Physical removal or insecticide
	Leaf and stem	- Caterpillars of some bagworm and the moth, *Streblote lipara*	- Physical removal or insecticide
Rhizophora mangle	Root	- Boring insect, *Sphaeroma terebans*	- Insecticide
Kandelia candel	Leaf	-Attack by the gastropod, *Littorinopsis intermedia*	- Physical removal or insecticide
Sonneratia spp.	Leaf	- Defoliator, *Streblote siva*	- Physical removal or insecticide
	Stem	- Bee hole borer, *Zeuzera conferta*	- Physical removal or insecticide

1996). For example, algae removal from the mudflat and the seedlings is done manually at low tide in Vietnam (Hong 1996). This activity is labor intensive and should be done with care to avoid damaging the seedlings during the process.

Success in controlling biotic factors is extremely variable and currently there is little successful means for their eradication. It appears that the best control is intensive care from foresters and regular tending after planting (Table 4.7). The sap of *Excoecaria agallocha* is known to either force barnacles to leave the mangrove seedlings or kill them. In several areas in Vietnam, foresters have tried to apply the sap of smashed *Excoecaria* stems on the mangrove stems colonized by barnacles at low tide without much success (Hong 1996). In Indonesia, several methods were tried to overcome problems from crab attacks. These included storing the seeds in a cool place for one week, painting the lower half of the propagule with tar, or covering the planted seeds with a bamboo tube (Soemodihardjo et al. 1996). It is believed that storing seeds for one week does not impair their survival and makes the propagules much harder; hence, they are not preferred by crabs. Painting propagules with tar was not successful because the paint did not last long enough in the water and, when the tar was completely washed away, the crabs returned. Table 4.7 gives a summary of pests found in mangrove plantations with potential treatment.

MAINTENANCE OF REFORESTED SITES. Mangrove areas require proper care and tending after planting to achieve successful restoration. Hong (1996) mentioned that tending of mangroves requires less effort and funds when compared to tending of terrestrial forests. The normal activities that must be undertaken are clearing debris, weeding, replacement planting, and thinning (Field 1996). Weeding is usually carried out periodically until the plantation is 5 years old (Chan 1996, Padron 1996). On ex-*Nypa* and *Acrostichum* stands, clearing can be done as much as twice a year (Hong 1996). These plants are well known for their capacity to grow fast so that within several months the new fronds may have covered the plantation area (Soemodihardjo et al. 1996). Thinning is important in order to ensure optimal growth of the mangrove trees (Untawale 1996). However, it can be avoided in the first few years by choosing a proper seedling spacing (Table 4.5; Siddiqi and Khan 1996). Sometimes,

TABLE 4.8: ACTIVITIES TO BE PURSUED AFTER THE ESTABLISHMENT OF A MANGROVE PLANTATION (ADAPTED FROM FIELD 1996).

Action	Comment
Monitor mangrove species that develop	Check correctness of original source of propagules and seeds. Wrong identification of seeds and propagules can lead to failure.
Monitor growth characteristics	Determinations could include: stem structure, node production, fruiting, and resistance to pests.
Monitor growth as a function of time	Common measurements are: density of seedlings or trees (number per ha), diameter at breast height (cm), height (m), and volume (m^3/ha). The annual increments of these parameters should be determined.
Record level of failure of seedlings	Provide a "scientific" reason for lack of success.
Record impact of pest and diseases	Note nature of pests and diseases and steps taken to eradicate the problem.
Record level of detritus accumulation	Note source of detritus and steps taken to minimize the problem.
Adjust density of seedlings to an optimum level	The degree of thinning, replanting or natural regeneration should be noted in detail. Subsequent growth should be monitored.
Record human impact such as illegal grazing, wood harvesting, and fishing	Note source of such external pressures and the steps that were taken to minimize the problems, e.g., fencing.
Assess characteristics of the restored mangrove ecosystem	This involves detailed measurements of the fauna, flora and physical environment of the new mangrove ecosystem and comparison with nearby similar undisturbed mangrove ecosystems.
Estimate cost of restoration project	The estimation of cost should include all aspects of the undertaking including the purchase of land and any legal costs.
Objectively judge the success of the restoration project against the original criteria that were established	This is rarely done but is an essential outcome.

because of occurrence of natural seedlings at the planting site, seedling density can be too high and thinning is then necessary (Soemodihardjo et al. 1996). Dead or unsuccessful seedlings should be replaced with new ones from natural mangroves or from a nursery. For all these activities to be done easily, the working trails used at the planting stage have to be maintained.

It is also necessary to implement pest and disease controls to guard against seed and stem borers, leaf defoliators, crabs, barnacles, and other animal attacks (Field 1996). Monitoring of survival rates, growth characteristics, and evaluation of the possible changes to the structure and function of existing mangrove ecosystems adjacent to the planting sites should be done (Lewis 1982). A summary of activities that should be pursued after the initial planting of a mangrove area is given in Table 4.8.

As already mentioned, it is important to have the support and understanding of local communities if successful restoration is to be implemented. Some interesting measures have been taken at the Can Gio reforested site in Vietnam, to ensure good management and protection of the replanted sites (Hong 1996). In addition to a small monthly salary, the guards receive 35% of the forest produce coming from thinning, between 3 to 5 ha of land per household to develop aquaculture or salt ponds, boats for forest protection, extra rewards for good protection of the forest, money to build houses on allocated land, and technical help through short training courses on thinning, reforestation, and aquaculture. A survey of eight typical households who received land and mangrove area for protection has indicated obvious improvement in their incomes. Furthermore, jobs have been created for a large number of poor peasants and fishermen in the form of collecting and sorting propagules, reforestation, guarding the forest during the day, cutting firewood when thinning or pruning, and catching small crabs, oysters, and clams on the forest floor. It appears that these measures were successful in educating the local villagers about the role of the mangrove ecosystem in providing direct as well as indirect benefits (Hong 1996).

COSTS AND BENEFITS OF REFORESTATION

The cost of restoration for mangrove is highly variable depending on factors such as local labor costs, the characteristics of the site (i.e., its accessibility and size), its proximity to propagule sources, and whether propagules, seedlings, or young trees are to be used (Saenger 1996, Snedaker and Biber 1996). Mangrove restoration projects often are very labor-intensive and conducted under difficult conditions. As a result, they can be quite expensive and costs are not limited to technical aspects but can involve land purchase and litigation (Field 1996). However, with relatively simple techniques and a strong commitment, there is a good chance that a healthy, self-sustaining mangrove ecosystem can be restored at previously damaged or degraded sites (Lewis 1982).

TABLE 4.9: WORK FORCE ESTIMATES FOR MANGROVE PLANT MATERIAL COLLECTION AND INSTALLATION (FROM THORHAUG 1998).

Species	Plant material	Task	Spacing	Man-hours
Rhizophora mangle	Propagules	Collection only		400 - 1,000/ha
	Propagule	Collection and installation	0.8 - 1.0 m	1,828/ha
	Seedlings (0.4-0.8 m)	Transplantation	1.0 m	3,098/ha
R. mangle, Avicennia germinans	Propagule	Collection and installation	0.8 - 1.0 m	457/ha
A. germinans, Laguncularia racemosa	Seedlings (0.3-1.9 m)	Transplantation	1.0 m	2,541/ha

TABLE 4.10: ESTIMATED COST (US$/HA) FOR PLANTING MANGROVES BY USING VARIOUS TECHNIQUES (FROM THORHAUG 1988).

Species and Technique	Spacing (m)		
	0.30	0.61	0.91
Rhizophora mangle			
Collected propagules	10,175 to 26,000	2,470 to 13,000	1,140 to 12,500
Purchased propagules	11,251 to 30,000	2,742 to 14,000	1,261 to 7,000
Transplanted 3-year-old trees			45,386
R. mangle, Avicennia germinans, Laguncularia racemosa			
Purchased 6-month-old seedlings	22,400 to 107,593	32 to 5,400	2,510 to 12,103
Purchased 3-year-old trees			40,755 to 216,130
A. germinans, L. racemosa			
Transplanted			11,459

Table 4.9 illustrates differences in work force estimates for planting mangroves according to the technique used. Person-hour estimates range from 450 to 1,800 per hectare for both collection and installation of propagules (Thorhaug 1988). From this limited data, it can also be seen that collection and installation of propagules require about half the time of transplantation of seedlings or small trees.

Thorhaug (1988) gives an average cost estimate of about US$1,236 per hectare to restore mangrove in developing nations (Table 4.10). Constanza et al. (1997) gave a total value for the mangrove ecosystem of US$11,029 per hectare per year. Therefore, it is of economic benefit for government, private sector, and citizen groups who use mangroves to restore them.

To date, only limited quantitative studies have been undertaken concerning the differences between restored and natural mangrove populations in a location of a similar size and density (Snedaker and Biber 1996). Few have noted marked differences between such sites if a proper time frame is considered and appropriate procedures for reforestation are followed (Thorhaug 1988). However, a survey of restored sites in Florida has shown that a large number of projects exhibited questionable merit (Lewis 1982, Snedaker and Biber 1996).

V RECOMMENDATIONS FOR MITIGATION OF SHRIMP AQUACULTURE IMPACTS ON MANGROVE

SUMMARY OF RECENT APPROACHES

Mangroves provide several direct and indirect benefits to shrimp aquaculture. These include a buffer zone to protect ponds against erosion and flooding, an improvement in coastal water quality, a natural habitat for shrimps, and opportunities to treat aquaculture effluents. However, it is important to recognize that shrimp farms can be successfully operated in areas where mangrove forest has never occurred. Furthermore, mangroves are of more benefit to shrimp farms managed extensively and located within mangrove forests than to intensive shrimp farms situated on the supra-tidal zone.

Recognizing the importance of mangroves within the coastal ecosystem, several "Codes of Practice" promoting sustainable development of coastal aquaculture operations have appeared over the last three years. The most notable one is the FAO Code of Practice for Responsible Fisheries with a section devoted to responsible development of aquaculture within national and transboundary aquatic ecosystems (refer to Appendix 2 for a copy of the section concerning aquaculture). The FAO code is a collection of principles for the wise management of aquaculture operations. These principles are based upon the recognized importance of biodiversity and the conservation and stewardship of ecosystems. Because conditions differ locally, such a code should be taken as general guidelines to be used as the basis for formulation of more specific codes applicable to a specific country or region. During the formulation of a national or regional code, collaboration among mangrove experts, environmentalists, coastal zone managers, aquaculturists, and other parties is necessary to ensure that it will reflect all concerns in relation to mangrove forests and adequate consideration of the social, economic, and ecological conditions.

Australia is in the process of developing its own environmental code of practice for shrimp farming. This procedure was initiated by the Australian Prawn Farmers Association which seeks to become acknowledged as an environmentally sustainable industry. The document aims to provide a mechanism for environmental regulation and options for management while staying relevant to Australian shrimp farmers, in a way that is flexible and focuses on outcomes (Donovan 1996). It is the objective of the Australian Prawn Farmers Association to pursue Ministerial approval for this Code of Practice, hoping to reduce the level of external regulation on the industry. It is believed that through this Code of Practice, the Australian prawn farming industry will be able to make substantial progress toward economic and environmental sustainability of the industry, while ensuring that farmers meet their "General Environmental Duty of Care" (Donovan 1996). One of the expected environmental outcomes of this code refers specifically to mangrove ecosystems: "All reasonable and practical measures must be adopted to ensure that a prawn farm operation does not lead to unacceptable direct or indirect impacts to mangrove ecosystems" (Donovan 1996).

The Global Aquaculture Alliance (GAA), an international non-governmental organization of aquaculture producers and marketers, has adopted the mission to foster production of high quality aquaculture products in environmentally sustainable systems. To promote greater environmental awareness within the shrimp industry and to protect mangrove forests from adverse impacts of coastal aquaculture, GAA has prepared a Mangrove Code of Practice (see Appendix 3 for a full copy). The purpose of the code is to present principles for protection of mangrove forests and their multiple uses while still permitting shrimp farming and other types of aquaculture within the coastal zone. The code is based on guiding principles leading to a list of management practices at the shrimp farm level that should prevent adverse effects on mangrove ecosystems. The objectives of the Mangrove Code of Practice are the following:

- Encourage the siting of shrimp farms outside mangrove areas to prevent the removal of mangrove, except as specified in an approved mangrove management plan.
- Operate existing farms in ways that do not damage mangrove areas.
- Assure that aquaculture operations do not infringe upon the rights of local inhabitants who depend for their livelihood upon mangrove resources.
- Require a mangrove management plan, developed by an appropriate local group, for use in siting new farms and a mangrove audit for existing farms. Only farms that comply with the standards of a mangrove management plan or mangrove audit will be in compliance with the Code.
- Develop a local monitoring program to verify the effectiveness of the mangrove management plan and mangrove audit.
- Encourage education on the importance of mangrove forests and encourage their protection.
- Ensure that coastal aquaculture complies with appropriate laws and regulations regarding the use of mangrove areas.

The expected outcomes from the development and adoption of this Mangrove Code of Practice include: sustainable aquaculture; better management of coastal resources; social harmony in coastal areas; conserved mangrove and better mangrove management; restoration of some degraded mangrove habitats; more people educated about mangroves; better public image for shrimp aquaculture; and possibly better prices for shrimp through environmental "labeling."

Codes of practice are increasingly being developed worldwide and aquaculturists are ready to adopt them. Such efforts should be encouraged and their development promoted. The shrimp industry should play an active role in the development of environmental codes and better management practices, if it wants to reduce the level of external regulation of the aquaculture production. The alternative to a proactive approach by the industry to develop production methods compatible with environmental protection will probably be more stringent governmental regulations.

MITIGATION OF ADVERSE IMPACTS THROUGH MANAGEMENT TECHNIQUES

FARM SITING, CONSTRUCTION, AND MAINTENANCE. Exten-sive shrimp farming in mangrove forests represents a major threat, although not the only one, and is likely the most significant contributor to mangrove loss through shrimp aquaculture in Asia. Given the importance in many countries of extensive farming to coastal shrimp production and the communities involved, efforts should be made to improve the social and economic value of mangrove use from such systems. Integrated aquaculture-mangrove forestry (silvofishery) offers one approach to conservation and utilization of the mangrove resources. This approach helps maintain a relatively high level of integrity within the mangrove area and capitalizes on the economic benefits of brackishwater aquaculture (Fitzgerald 1997). Diversification to mixed culture systems and partial or complete reforestation of unproductive or degraded farming areas should also be considered.

Mangrove forests are not optimal sites for aquaculture ponds. Soils in such locations often are highly acidic and may contain large amounts of organic matter. It is difficult to drain and dry soil to permit use of standard construction techniques. Water exchange by tidal flow in the creeks and channels of mangrove wetlands is incomplete and pond effluents may not be washed completely away when discharged. As a result, it is difficult to prevent cross-contamination of intake water and discharge water on farms located in the inter-tidal zone. Mangroves are located in low lands and pond drainage in such areas may not be complete. Where farms are located behind the mangrove fringe, the water supply and discharge canals should be located to eliminate negative impacts on local hydrology, and in such circumstances some method for mitigating the impact on mangroves may be required.

To summarize, the following criteria should be applied when choosing the location of new shrimp ponds in relation to mangrove ecosystems:

- Locate new shrimp ponds outside mangroves or other wetlands of significant ecological and social values.
- Roads, canals and other infrastructures should not change the natural hydrology in and around mangroves.
- Where mangrove must be removed for access, replanting in other available areas with equivalent ecological value should be done as mitigation procedure.
- No net loss of mangrove should be permitted.

Impacts on mangrove forests and the larger environment can happen during farm construction and farm operation phases. It is important to minimize potential disturbance of mangroves close to the farm site during both phases.

During construction, soil erosion can occur because of rain and runoff, and nearby mangrove stands could be adversely affected by flooding with water with high concentrations of suspended soil particles. The risk of erosion can be reduced if construction is done during the dry season and if surface runoff is excluded from construction areas. Precise cut and fill calculations will prevent piles of excess soil and reduce the necessity to create borrow pits to obtain earth fill. Good compaction of pond levees and canals is necessary. Slopes of embankment and canal sides should be adequate to prevent erosion. Top soil can be stockpiled during construction and placed back on above-water parts of canals and embankments and coverage by grass species tolerant to the prevailing environmental conditions at the farm location encouraged. This practice can prevent embankment erosion from direct rain and runoff and adverse impact on surrounding mangrove stands. If pockets of acid-sulfate soil are excavated in the construction process, the potential problem of acid formation and contamination through runoff should be avoided by only using this soil as inside fill for embankments. It should then be covered with well-compacted, good quality soil and not exposed to air so as to avoid oxidation and development of acidic runoff.

During the construction of access roads and water supply or drainage canals, there is the potential of isolating mangrove stands from normal tidal inundation or freshwater runoff. To prevent this, the farm layout should be designed to ensure normal hydrological conditions in and around the mangrove areas. If a road or canal is located in a manner that might interfere with the local hydrology, culverts of sufficient size should be installed under the road or canal to ensure adequate water exchange.

Shrimp farm operation should implement the following guidelines to reduce negative impacts on adjacent mangroves:

- Proper attention should be given to maintenance of embankments and canals in order to reduce damage to these structures and prevent high suspended solid concentrations in outflowing water to be discharged in or near mangrove areas.
- Water should be released slowly during the final stage of harvest to avoid erosion of pond bottoms by outflowing waters. Sediment traps in canals and settling basin may be installed to reduce solid concentrations in final effluents.
- Pond effluents should not be discharged into stagnant areas of mangroves where water logging will cause suffocation of the mangroves.
- Sediments and/or garbage should not be disposed of in mangrove areas.
- Dead cultured animals should be disposed of in a sanitary manner so as to avoid spread of disease into natural shrimp populations.
- Use of drugs and chemicals should be limited. Active piscicides should not be discharged through mangroves.
- Pollution of mangroves through fuel or oil leaks should be avoided.

When considering the development of coastal aquaculture, proper attention should also be given during the planning process to potential negative social interactions. Shrimp farms should be constructed and operated in such a way to avoid decline in mangrove productivity. Coastal communities harvest a wide range of natural products from the mangroves and surrounding waters, and their access to mangroves should not be restricted by the development of shrimp farms.

MANGROVE RESTORATION IN ABANDONED PONDS. There is an increasing interest in rehabilitation and restoration of idle, unproductive, or abandoned shrimp ponds. In some countries, restoration programs are already starting in shrimp farming areas (Thailand, Vietnam, and Ecuador). In general terms, the need for restoration of mangrove ecosystems in relation to aquaculture may arise under the following conditions:

- Restoration of degraded areas or abandoned ponds and surrounding areas to mangroves.
- Restoration of extensive ponds to silvofishery enterprises.
- Restoration of areas in compensation for mangroves removed for water supply and drainage systems for farms located behind mangroves.

AQUACULTURE INCLUSION IN COASTAL MANAGEMENT PLANS. Mangroves are clearly an important resource, providing benefits to aquaculturists and other people living in coastal areas. Because aquaculture is only one of the activities occurring in coastal areas, and it may affect and be affected by other activities, the development of aquaculture needs to be seen within an integrated coastal management context. The approach of many countries to accelerating mangrove destruction is to adopt more stringent and unenforceable regulations designed to prohibit or severely limit all human activities in mangrove areas. An alternative strategy that is rapidly gaining support among both government agencies and the public, is the development of mangrove management techniques that promote a diversity of sustainable activities within the mangroves, organized and administrated at the community level.

The formulation of community-based coastal resource management plans should include a zoning process where identification and protection of key mangrove areas are achieved, as well as the identification of zones for sustainable developments. The aim of zoning is to establish clearly demarcated geographic zones with specific permissible and non-permitted uses that could include identification of zones for aquaculture development. While such zones can be a potentially important means of protecting mangrove resources, various examples in Asia show that they can be difficult to enforce. Such problems have led to more focus on local level participation in identification, protection, and sustainable exploitation of mangrove forests. It is evident that the government has a clear role in policy for land use planning and designation of zones, but the shrimp industry can play an important role in encouraging the proper identification of key mangrove resources and development of management plans.

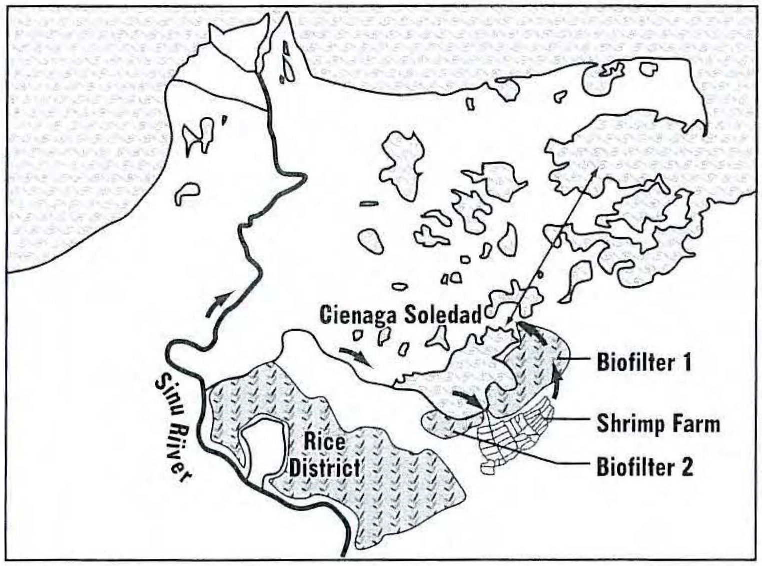


Figure 5.1. General view of the estuary with shrimp farm and rice district locations.

CASE EXAMPLE OF BENEFICIAL MANGROVE MANAGEMENT

Despite a widespread view to the contrary among conservationists, research in southern Thailand and elsewhere has shown that mangroves can be planted successfully in shrimp waste sludge directed into holding areas in the intertidal zone (Macintosh 1996). In addition, recent research has shown that mangrove forests and other wetlands are highly efficient in enhancing the removal of solids and nutrients from aquaculture effluents (Robertson and Phillips 1995, Schwartz and Boyd 1995). This opens up the potential for aquaculturists operating farms located on appropriate coastal sites to promote green belts of mangroves around the seaward edge of their ponds and use them as effluent treatment tools. A trial started in June 1996 on a shrimp farm along the Caribbean coast of Colombia.

The mangrove in this particular estuary is composed of five species: *Rhizophora mangle*, *Avicennia germinans*, *Conocarpus erectus*, *Laguncularia racemosa*, and *Acrostichum aureum*. Trees of *R. mangle* are found on the sea front and along river banks influenced by sea water and *C. erectus* will prefer the river banks in areas with relatively lower salinity. Both *A. germinans* and *L. racemosa* are found behind these fringe zones, in basin mangrove areas. The mangrove fern, *A. aureum*, is dominant on higher land, at the limit with the upper terrestrial ecosystem. This zonation pattern is similar to that reported for other mangroves in the Caribbean area (McKee 1995).

The shrimp farm is located some 10 km inside the estuary along a bay with little direct influence from the Caribbean Sea (Fig. 5.1). In the same area, the Colombian government associated with the World Bank developed a large project of intensive rice culture in the 1980s, with the majority of the runoff draining into the estuary (Fig. 5.1). The shrimp farm started in 1986 and developed to about 160 ha of pond surface over the years. The production system is semi-intensive and the yield varies between 2,500 and 3,500 kg/ha. In 1994, the shrimp farm experienced for the first time problems with Cyanobacteria development in the production ponds. These algae are associated in shrimp ponds with low salinity and high dissolved nutrient concentrations. Some species are responsible for producing compounds that impart a musty or earthy-muddy taste to cultured shrimp. This phenomenon is referred to as off-flavor and postpones shrimp harvest until the shrimp recover an acceptable flavor. These algae were also flourishing in the water supply for the shrimp farm, Cienaga Soledad (Fig. 5.1).

Based upon information gathered at the time, it seemed that the estuary, in particular Cienaga Soledad, has been undergoing eutrophication from runoff of the newly intensive rice production development and from the shrimp farm effluents. Water circulation within the estuary, and especially the intrusion of sea water during the rainy season, is moderate at best. These conditions favor the development of Cyanobacteria blooms and repeatedly, during the rainy season, caused off-flavor problems in the farmed shrimp. The following long-term possibilities were presented to the farmer:

- Divert runoff from the rice district around the estuary to reduce the major input of nitrogen and phosphorus into the estuary; or

- Divert shrimp farm effluents through the mangrove area to allow sedimentation and other natural purification processes to enhance the quality of the effluent before it flows back into Cienaga Soledad, the water source. In this last case, providing greater vegetation density within the flow path was also recommended.

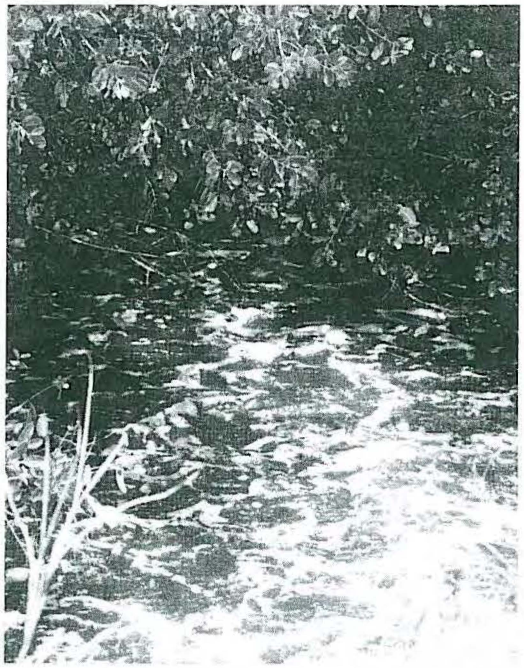


Figure 5.2. Effluents from the shrimp farm entering Biofilter 1.

In June 1996, the farmer decided to direct the shrimp farm effluents through mangrove stands dominated by *Acrostichum* (80%) and *Rhizophora* (20%). After naturally entering the mangrove area (Fig. 5.2), now referred to as "Biofilter 1," the flow of effluents drained into Cienaga Soledad and canal Palermo, a canal connected with the Caribbean sea through a network of lagoons and natural channels (Fig. 5.1). After an experimental phase, the farmer decided to build a canal along the southern side of Biofilter 1 to allow the effluent to enter the mangrove at different locations (Fig. 5.3). This would force dispersion into Biofilter 1 which would enhance the natural flow pattern and allow for higher efficiency in effluent treatment. Some areas inside Biofilter 1 were not colonized by mangrove trees and approximately 10 hectares were reforested with *Rhizophora*, in an attempt to increase the mangrove diversity. Nursery grown seedlings were transferred and held in place with branches to favor good rooting. A little more than a year after reforestation, it was estimated that the young seedlings were adapting well to the site and that their growth rate was satisfactory and comparable to natural stands. In the next development phase, part of the farm discharge penetrating Biofilter 1 was directed into a second mangrove area referred to as "Biofilter 2" to increase the treatment area (Fig. 5.3). The connection between the two biofilters was through floating plastic tubes crossing the entrance canal of the shrimp farm (Fig. 5.4). The discharge from Biofilter 2 was subdivided into different natural channels along a 3 km front in the Cienaga Soledad. The total mangrove surface for the two biofilters was around 250 ha.

Preliminary results from weekly water analyses taken in 1995 and 1997 indicated a decrease in inorganic nutrient loading from the shrimp farm effluents in the estuary (Table 5.1). However, this experimental approach (comparing the concentration of dissolved inorganic nutrients entering and exiting the biofilter) does not account for the particulate organic matter resulting from live plankton and detritus contained in the effluents. Effluents from aquaculture ponds are often more concentrated in solids and organic matter than entering waters (Ziemann et al. 1992). Removal of substances from water by mangrove wetlands involves a number of processes, including sedimentation of suspended particles, filtration of suspended particles by plant materials, uptake of nutrients by plants and bacteria,

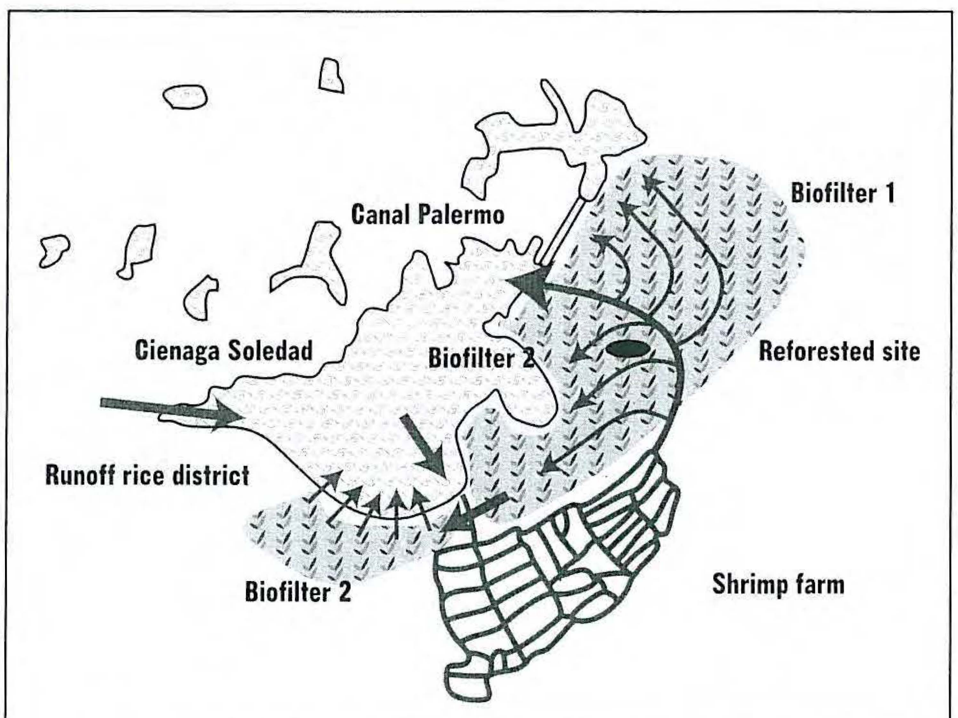


Figure 5.3. Detailed schematic of the biofilters with corresponding hydrological flow patterns.

TABLE 5.1: ANNUAL AVERAGE FOR WATER QUALITY PARAMETERS BEFORE AND AFTER THE INITIATION OF THE BIOFILTER SYSTEM. ANNUAL AVERAGES FOR A SAME LOCATION FOLLOWED BY DIFFERENT SUPERSCRIPT DIFFER AT THE P = 0.10 LEVEL AS DETERMINED BY THE STUDENT'S T-TEST.

	Effluent discharge (entering biofilter 1)		Canal Palermo (exiting biofilter 1)		Cienaga Soledad	
	1995	1997	1997	1995	1995	1997
Soluble Reactive Phosphorus (mg/L)	0.22a	0.09b	0.26a	0.12a	0.15a	0.16a
Total Ammonia Nitrogen (mg/L)	0.22a	0.08b	0.18a	0.05b	0.09a	0.07a
Nitrate-Nitrogen (mg/L)	0.8a	0.5b	0.7a	0.5b	0.6a	0.5a

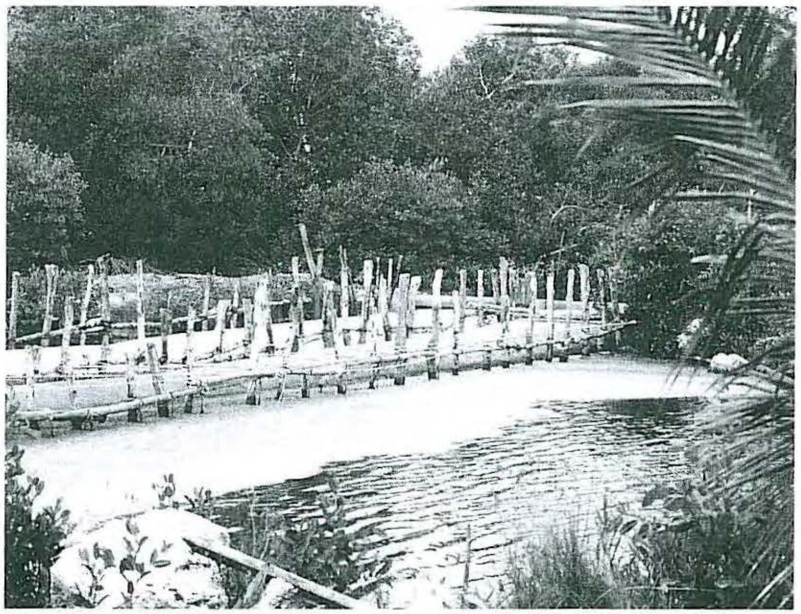


Figure 5.4. Floating plastic tubes connecting the two biofilters.

decomposition of organic matter, denitrification, nitrification, and adsorption of ions by the soil. Previous studies have shown that wetlands remove large amounts of potential nutrients from the water through non-biological processes of sedimentation, filtration, and soil adsorption (Schwartz and Boyd 1995). Although this preliminary study does not document it, presumably the majority of the particulate matter contained in the shrimp effluents is lost through sedimentation before reaching the mangrove estuary.

Results from the study show no significant change in inorganic nutrient concentrations in the main bay, Cienaga Soledad. Apparently the discharge from the rice production area still contributes largely to dissolved nutrient inputs into the estuary. Monthly water quality measurements at the major discharge point coming from the rice district indicate high dissolved inorganic nutrient concentrations, mainly as soluble phosphorus (0.42 mg/L). In addition this riverine mangrove ecosystem is naturally rich and contributes its own input of nutrients to the estuarine water. A combination of freshwater runoff and high inputs of nutrients from both upland and estuarine sources is responsible for the high productivity often associated with these ecosystems (Mitsch and Gosselink 1993). In this particular case, the production of guano by a very large population of resident birds heavily contributes to the richness of the water inside the mangrove wetland. Average concentrations for water samples taken from a central location inside Biofilter 1 are the following: soluble reactive phosphorus = 0.46 mg/L, total ammonia nitrogen = 0.91 mg/L, and nitrate = 0.7 mg/L. These concentrations reflect the richness of the mangrove and its potential for natural contribution to the estuary enrichment.

The problems associated with uncontrolled Cyanobacteria development in the production ponds disappeared, even during low salinity episodes. Probably the shrimp farm effluents are transformed inside the mangrove biofilter and stop contributing to the estuary eutrophication. However, the continuous inputs from the rice district continue to present a long-term risk of eutrophication to the estuary. By using the mangrove as a biofilter for the farm effluents, the problems seem to be under control at the moment.

This example illustrates one of the direct benefits of mangroves to shrimp aquaculture. It suggests that mangrove habitats could be used to treat effluent from shrimp farms and enhance coastal water quality. Because these habitats require almost no maintenance by the farmers, they are not prone to mechanical failure or fatigue and even should improve with age. However, monitoring of the mangroves inside the biofilters should continue to ensure that species composition, biodiversity, and the associated fauna are not adversely affected. Further research is still necessary (e.g., establish relative areas of shrimp pond and mangrove required for effective treatment and estimate to what degree mangroves can absorb nutrients, especially nitrogen and phosphorus) before such a water treatment system is recommended in various locations. It is increasingly being recognized that such an approach offers interesting future possibilities and should be researched (Macintosh 1996).

MANGROVES AND SHRIMP AQUACULTURE – A PERSPECTIVE

Along with fulfilling important functions in coastal ecosystems, mangroves may provide several direct and indirect benefits to shrimp farming, including the following:

- Water quality can be improved through sedimentation and absorption of nutrients, heavy metals, and pesticides.
- Mangroves are natural habitats for shrimps and contribute to the provision of post-larvae, juveniles, and broodstock.
- Aquaculture ponds located behind mangrove buffers may be protected against erosion and storm surges.
- Roots of mangrove trees can stabilize banks of effluent and intake canals.
- Mangroves support a detritus-enriched microbial foodweb which can promote productivity of nearshore fisheries and extensive aquaculture ponds.

Mangroves are not suitable areas for semi-intensive and intensive shrimp aquaculture, because of poor soils, higher construction costs, poor drainage and harvesting conditions, and higher risk of failure. However, shrimp farming can be conducted in areas away from mangrove forests. Past removal of mangroves for establishment of shrimp ponds has led to user conflicts and negative social impacts on local communities. However, coastal aquaculture can play an important economic role by creating new economic niches, generating employment, more effectively utilizing local resources, and providing local sources of high-quality food and opportunities for productive investment in the local economy (Bailey 1997). All economic activities, including aquaculture, have environmental impacts. Some practices, however, are more harmful than others. A primary goal of aquaculturists and shrimp farmers should be to commit to environmentally sustainable and more economically viable enterprises (Clay 1997).

Conflicts associated with aquaculture are not restricted to mangrove wetlands or shrimp aquaculture. To mention only one other example: producers of salmon and shellfish have been blamed by local residents for altering the aesthetic beauty of coastal areas, taking control over productive coastal waters, impairing navigation, and introducing exotic diseases which threaten local stocks (Bailey 1997). Modern aquaculture is only about 25 years old and is still in its adolescence compared with other animal husbandry industries. One challenge for the aquaculture industry is to change an existing perception that aquaculture may be inherently and necessarily unsustainable, a perception created by early mistakes made by the industry and reinforced by misinformation spread by the media (Pillay 1996). Many new and promising technologies and management practices are being developed to reduce environmental impact of aquaculture operations and increase efficiency and sustainability. Through experimentation and carefully designed studies, information is generated demonstrating that proper aquaculture farm management practices ensure sustainability. Such information should be spread to the large community, including aquaculturists, governmental agencies, development agencies, and non-govermental organizations.

Shrimp farmers cannot be expected to solve all the environmental problems affecting mangrove resources. Governments should initiate and further develop strategies for a balanced use of coastal resources for various developments, including mangrove conservation and coastal aquaculture. Shrimp farmers should be encouraged to promote efforts to rehabilitate abandoned shrimp farms that have reverted to public ownership and to prevent further loss of ecologically important mangroves. Mangrove experts should be actively encouraged to cooperate in the identification of appropriate reforestation strategies for sites selected. Hopefully, this document will be of help in future restoration efforts by presenting basic techniques for implementing reforestation programs. There is a general lack of awareness and education among the shrimp farming industry about the importance of mangrove conservation and the value of mangroves to coastal communities and sustainable aquaculture development. More information should be collected and disseminated on successful case studies of mangrove management and benefits for aquaculture.

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APPENDIX 1: LIST OF MANGROVE SPECIES BY REGIONS (SPALDING ET AL. 1997).

	South and Southeast Asia	Australasia	The Americas	West Africa	East Africa Middle East
Acanthus ebracteatus	•	•			
Acanthus ilicifolius		•	•		
Acrostichum aureum	•	•	•	•	•
Acrostichum speciosum	•	•			
Aegialitis annulata		•	•		
Aegialitis rotundifolia	•				
Aegiceras corniculatum	•	•			
Aegiceras floridum		•			
Avicennia alba		•	•		
Avicennia bicolor			•		
Avicennia germinans			•	•	
Avicennia integra		•			
Avicennia marina		•	•		•
Avicennia officinalis	•	•			
Avicennia rumphiana	•	•			
Avicennia schaueriana			•		
Bruguiera cylindrica	•	•			•
Bruguiera exaristata	•	•			
Bruguiera gymnorrhiza	•	•			•

APPENDIX 1: LIST OF MANGROVE SPECIES BY REGIONS (SPALDING ET AL. 1997).

	South and Southeast Asia	Australasia	The Americas	West Africa	East Africa Middle East
Bruguiera hainesii	•	•			
Bruguiera parviflora	•	•			
Bruguiera sexangula	•	•			
Camptostemon philippinense	•				
Camptostemon schultzii	•	•			
Ceriops australis		•			
Ceriops decandra	•	•			
Ceriops tagal	•	•			•
Conocarpus erectus			•	•	
Cynometra iripa	•	•			
Diospyros ferrea		•			
Dolichandrone spathacea	•	•			
Excoecaria agallocha	•	•			•
Excoecaria indica	•				
Heritiera fomes	•				
Heritiera globosa	•				
Heritiera littoralis	•	•			•
Kandelia candel	•				
Laguncularia racemosa			•	•	
Lumnitzera littorea	•	•			
Lumnitzera racemosa	•	•			•
Lumnitzera x *rosea*	•	•			
Mora oleifera			•		
Nypa fruticans	•	•	•	•	
Osbornia octodonta	•	•			
Pelliciera rhizophorae			•		
Pemphis acidula	•	•			•
Rhizophora apiculata	•	•			
Rhizophora harrisonii			•	•	
Rhizophora mangle			•	•	
Rhizophora mucronata	•	•			•
Rhizophora racemosa			•	•	•
Rhizophora samoensis		•			
Rhizophora stylosa	•	•			
Rhizophora x *lamarckii*	•	•			
Rhizophora x *selala*		•			
Scyphiphora hydrophyllacea	•	•			
Sonneratia alba	•	•			•
Sonneratia apetala	•				
Sonneratia caseolaris	•	•			•
Sonneratia griffithii	•				
Sonneratia lanceolata	•	•			
Sonneratia ovata	•	•			
Sonneratia x *gulngai*	•	•			
Sonneratia x *urama*	•	•			
Tabebuia palustria			•		
Xylocarpus granatum	•	•			•
Xylocarpus mekongensis	•	•			

APPENDIX 2: AQUACULTURE PART OF THE FAO CODE OF CONDUCT FOR RESPONSIBLE FISHERIES

ARTICLE 9 - AQUACULTURE DEVELOPMENT

I. Responsible development of aquaculture, including culture-based fisheries, in areas under national jurisdiction

States should establish, maintain and develop an appropriate legal and administrative framework which facilitates the development of responsible aquaculture.

States should promote responsible development and management of aquaculture, including an advance evaluation of the effects of aquaculture development on genetic diversity and ecosystem integrity, based on the best available scientific information.

States should produce and regularly update aquaculture development strategies and plans as required, to ensure that aquaculture development is ecologically sustainable and to allow the rational use of resources shared by aquaculture and other activities.

States should ensure that the livelihoods of local communities, and their access to fishing grounds, are not negatively affected by aquaculture developments.

States should establish effective procedures specific to aquaculture to undertake appropriate environmental assessment and monitoring with the aim of minimizing adverse ecological changes and related economic and social consequences resulting from water extraction, land use, discharge of effluents, use of drugs and chemicals, and other aquaculture activities.

II. Responsible development of aquaculture including culture-based fisheries within transboundary aquatic ecosystems

States should protect transboundary aquatic ecosystems by supporting responsible aquaculture practices within their national jurisdiction and by cooperation in the promotion of sustainable aquaculture practices.

States should, with due respect to their neighboring States and in accordance with international law, ensure responsible choice of species, siting and management of aquaculture activities which could affect transboundary aquatic ecosystems.

States should consult with their neighboring States, as appropriate, before introducing non-indigenous species into transboundary aquatic ecosystems.

States should establish appropriate mechanisms, such as databases and information networks to collect, share and disseminate data related to their aquaculture activities to facilitate cooperation on planning for aquaculture development at the national, subregional and global level.

States should cooperate in the development of appropriate mechanisms, when required, to monitor the impacts of inputs used in aquaculture.

III. Use of aquatic genetic resources for the purpose of aquaculture including culture-based fisheries

States should conserve genetic diversity and maintain integrity of aquatic communities and ecosystems by appropriate management. In particular, efforts should be undertaken to minimize the harmful effects of introducing non-native species or genetically altered stocks used for aquaculture including culture-based fisheries into waters, especially where there is a significant potential for the spread of such non-native species or genetically altered stocks into waters under the jurisdiction of other States as well as waters under the jurisdiction of the State of origin. States should, whenever possible, promote steps to minimize adverse genetic, disease and other effects of escaped farmed fish on wild stocks.

States should cooperate in the elaboration, adoption and implementation of international codes of practice and procedures for introductions and transfers of aquatic organisms.

States should, in order to minimize risks of disease transfer and other adverse effects on wild and cultured stocks, encourage adoption of appropriate practices in the genetic improvement of broodstocks, the introduction of non-native species, and in the production, sale and transport of eggs, larvae or fry, broodstock or other live materials. States should facilitate the preparation and implementation of appropriate national codes of practice and procedures to this effect.

States should promote the use of appropriate procedures for the selection of broodstock and the production of eggs, larvae and fry.

States should, where appropriate, promote research and when feasible, the development of culture techniques for endangered species to protect, rehabilitate and enhance their stocks, taking into account the critical need to conserve genetic diversity of endangered species.

IV. Responsible aquaculture at the production level

States should promote responsible aquaculture practices in support of rural communities, producer organizations and fish farmers.

States should promote active participation of fish farmers and their communities in the development of responsible aquaculture management practices.

States should promote efforts which improve selection and use of appropriate feeds, feed additives and fertilizers, including manures.

States should promote effective farm and fish health management practices favoring hygienic measures and vaccines. Safe, effective and minimal use of therapeutants, hormones and drugs, antibiotics and other disease control chemicals should be ensured.

States should regulate the use of chemical inputs in aquaculture which are hazardous to human health and the environment.

States should require that the disposal of wastes such as offal, sludge, dead or diseased fish, excess veterinary drugs and other hazardous chemical inputs does not constitute a hazard to human health and the environment.

States should ensure the food safety of aquaculture products and promote efforts which maintain product quality and improve their value through particular care before and during harvesting and on-site processing and in storage and transport of the products.

APPENDIX 3: MANGROVE CODE OF MANAGEMENT PRACTICES ESTABLISHED BY THE GLOBAL AQUACULTURE ALLIANCE

Purpose

The code is designed to foster greater environmental awareness within the shrimp farming industry to assure continued protection of mangrove forests from potentially adverse impacts of coastal aquaculture. Recognizing the multitude of different conditions impacting mangroves in different countries and regional locations, this code is to be interpreted as a flexible set of criteria to be used to assist any and all interested parties in formulating codes, regulations, and principles for protecting mangrove forests.

Relationship to Guiding Principles

The Code helps to achieve the following Guiding Principles for companies and individuals engaged in aquaculture, singularly and collectively:

They shall cooperate with national, regional and local governments in the development and implementation of policies, regulations and procedures necessary and practicable to achieve environmental, economic and social sustainability of aquaculture operations.

They shall utilize only those sites for aquaculture facilities whose characteristics enable long term sustainable operation with minimum ecological effects, particularly avoiding destruction of mangroves and other environmentally sensitive areas.

They shall strive for continuing improvements in feed use and shall use therapeutant agents judiciously in accordance with appropriate regulations.

They shall take all steps practicable to achieve environmental, economic, and social sustainability.

Management Practices

It shall be the objective of all adherents to this code to not harm, but whenever possible preserve and even enhance the biodiversity, and preservation of mangrove ecosystems. The following practices will ensure mangrove ecosystems protection:

Whenever possible, shrimp farms should not be developed within mangrove ecosystems.

Whenever mangrove reduction is necessary for the growth of shrimp aquaculture, a re-forestation commitment of no net loss of mangroves shall be initiated.

Farms in operation will continue ongoing environmental assessments to recognize and alleviate any possible negative impacts.

All non-organic and solid waste materials should be disposed of in an environmentally responsible manner, and waste water and sediments shall be discharged in manners not detrimental to mangroves.

The shrimp aquaculture industry pledges to work in concert with governments to develop sound regulations to enhance the conservation of mangroves.

Shrimp aquaculture industries will promote measures ensuring the traditional livelihood of local communities in mangrove areas.