Review

Malaysian Mangrove Forests and their Significance to the Coastal Marine Environment

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Abstract

Mangrove forests are one of the most productive and bio-diverse wetland environments on earth. Yet these unique coastal tropical forest environments are among the most threatened habitats in the world. Some key progress points in mangrove conservation, restoration, and research in Malaysia are highlighted. Based on an intensive literature review, the ecology and ecological management, distribution and areas of existing mangroves in the world and Malaysia, issues associated with mangrove conservation and restoration are discussed. Growing in the intertidal areas and estuary mouths between land and sea, mangroves provide critical habitat for diverse marine and terrestrial flora and fauna. Important for the flora and fauna is the opportunity to continue living in a sustainable environment and in suitable conditions. A potential stand is the place that obtains the possibility of germination and establishment of a plant species according to their physical, chemical, and biological demands. In many cases it is seen that because of unsuitable selection of site and species, afforestation and reforestation projects are forced to fail after spending time, cost, and labor. The population boom and rapid economic developments have greatly reduced mangrove areas in Malaysia despite the Malaysian government launching a series of programs to protect mangroves in the 1980s and establishing mangrove ecosystems as high-priority areas for improving environmental and living resource management. The issues, threats, and significant values of mangroves also were highlighted. A more systematic protection strategy using ecological engineering management-based, active restoration and rehabilitation measurements still are urgently needed in order to preserve these valuable resources in Malaysia.

Introduction

Malaysia is a maritime country with more than 4,800 km of coastline. The coastal forests play valuable roles in foreshore protection, reducing coastal erosion and reducing the impacts of storm surge. Under these circumstances, the coastal forests in Malaysia represent an important ecosystem and are accorded a high priority in maintaining protective and productive functions along the coastal lines. Recognizing the crucial role of coastal forests, including mangrove forests, freshwater swamp forests, riparian forests, and beach forests, the Malaysian government is very concern about the importance of their existence and is fully committed to sustainably managing, rehabilitating and conserving these forests.

The 2004 December 26th tsunami caused enormous environmental damage to the northwestern coast of Peninsular Malaysia. Damage assessments indicate that

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areas with relatively intact trees along the shoreline were less affected by the tsunami. The tsunami event has made the tree planting efforts initiated in early 1980s by the Forestry Department of Peninsular Malaysia (FDPM) very much relevant and important for coastline protection in the future. Under the Ninth Malaysian Plan (2006-10) FDPM, in collaboration with other agencies and related research institutions, will enhance its efforts to continue to embark on the tree planting program along the coastal areas in the country. FDPM is heading one of the technical committees, namely "Planning and Implementation Technical Committee on National Tree Planting Program along Coastal Areas." In the long term, this program is not only to enhance the coastline protection role but also provides considerable support to political, social, economic, and ecological stability, as well as increasing the goods and services of mangroves in the future.

The role of mangroves, as nursery and feeding areas, in the enrichment of coastal waters, in the stabilization of the shoreline, and in trapping silt and wastes from upland runoff, is repeatedly being threatened by suggestions for reclamation, whether for aquaculture, agriculture, or development projects [1]. Proposals for such alternatives should only be judged after taking into account the environmental subsidies involved and possible losses in energy transformation steps. Assurance is needed that renewable resources and other environmental capital will not be sacrificed. Given the enormous benefits of mangrove forests, the objective of this paper is to highlight the urgent need of proper management and conservation to ensure the continued existence of mangrove forests in Malaysia

What and where are the World's Mangrove Forests?

Mangroves can be broadly defined as woody vegetation types occurring in marine and brackish environments [2]. Mangrove trees have intertwined stilt roots that arc into shallow waters, while finger-like nubs rise above the water surface to breathe. Mangrove forests have special adaptations that help them survive the brackish conditions of tidal zones. They are a unique ecosystem generally found along sheltered coasts, where they grow abundantly in saline soil and brackish water subject to periodic fresh- and salt-water inundation. Mangrove trees have specific characteristics such as tough root systems, special bark and leaf structures, and other unique adaptations to enable them to survive in their habitat's harsh conditions. The habitat is soft, silty and shallow, coupled with the endless ebb and flow of water, providing very little support for most mangrove plants, which have aerial or prop roots (known as pneumatophores, or respiratory roots) and buttressed trunks. They are generally restricted to the tidal zone, which is the strip of coast starting from the lowest low water level up to the highest high water level. In Peninsular Malaysia, mangrove forests are found mainly on the sheltered coasts, estuaries, rivers, and some near-shore islands. Mangrove forests support a diverse range of animals and plants and are repositories for a vast array of biological diversity. The importance of mangrove forests in providing invaluable goods and services both in economics and environmental terms are well understood and documented.

Mangroves, the only woody halophytes living at the confluence of land and sea, have been heavily used traditionally for food, timber, fuel, and medicine, and presently occupy about 181,000 km^2 of tropical and subtropical coastline. Over the past 50 years, approximately one-third of the world's mangrove forests have been lost, but most data show variable loss rates, and there is considerable margin of error in most estimates. Mangroves are a valuable ecological and economic resource, being important nursery grounds and breeding sites for birds, fish, crustaceans, shellfish, reptiles, and mammals; a renewable source of wood; accumulation sites for sediment, contaminants, carbon and nutrients; and offer protection against coastal erosion. The destruction of mangroves is usually positively related to human population density. Major reasons for destruction are urban development, aquaculture, mining and overexploitation for timber, fish, crustaceans and shellfish. Over the next 25 years, unrestricted clear felling, aquaculture, and overexploitation of fisheries will be the greatest threats, with lesser problems being alteration of hydrology, pollution and global warming. Loss of biodiversity is, and will continue to be, a severe problem as even pristine mangroves are species-poor compared with other tropical ecosystems. The future is not entirely bleak. A world without mangroves has been clearly criticized [3]. It has also been emphasized that the loss of foundation mangrove species is a consequences of the structure and dynamics of forest ecosystems [4]. The number of rehabilitation and restoration projects is increasing worldwide with some countries showing increases in mangrove area. The intensity of coastal aquaculture appears to have leveled off in some parts of the world. Some commercial projects and economic models indicate that mangroves can be used as a sustainable resource, especially for wood. The brightest note is that the rate of population growth is projected to slow during the next 50 years, with a gradual decline thereafter to the end of the century. Mangrove forests will continue to be exploited at current rates to 2025, unless they are seen as a valuable resource to be managed on a sustainable basis. After 2025, the future of mangroves will depend on technological and ecological advances in multi-species silviculture, genetics, and forestry modeling, but the greatest hope for their future is for a reduction in human population growth [5].

Range declines for all mangrove species from habitat loss and localized threats are occurring in all tropical coastal regions of the world [6]; however, some regions show greater losses than others. For example in Panama, it was reported that large-scale damage to mangrove forests was simply due to large oil spills [7]. Unlike many other forests, mangrove forests consist of relatively few species, with 30-40 species in the most diverse sites and only one or a few in many places [8]. Globally, mangrove biodiversity is highest in the Indo-Malay Philippine Archipelago (Fig. 1), with between 36 and 46 of the 70 known mangrove species occurring in this region. Although less than 15% of

species present in this region are in threatened categories (Fig. 2), the Indo-Malay Philippine Archipelago has one of the highest rates of mangrove area loss globally, with an estimated 30% reduction in mangrove area since 1980 [6].

Mangroves in this region are primarily threatened by clearing for the creation of shrimp and fish ponds [9]. For example, approximately half of the 279,000 ha of mangroves in the Philippines lost from 1951 to 1988 were developed into fish/shrimp culture ponds [10]. *Camptostemon philippinense* (listed as endangered) has an estimated 1,200 or fewer individuals remaining due to the extensive removal of mangrove areas for both aquaculture and fuelwood within its range. The Endangered *Heritiera globosa* has the most restricted distribution in this region (extent of occurrence below 5,000 km^2), as it is only known from western Borneo, where it's patchily distributed; pri-

marily riverine habitat has been extensively cleared by logging activities and for the creation of timber and oil palm plantations.

Geographic areas with a high numbers of mangrove species at elevated risk of extinction are likely to exhibit loss of ecosystem function, especially in areas of low mangrove diversity. Globally, the highest proportion of threatened mangrove species is found along the Atlantic and Pacific coasts of Central America. Four of the 10 (40%) mangrove species present along the Pacific coasts of Costa Rica, Panama, and Colombia are listed in one of the three threatened categories, and a fifth species, *Rhizophora samoensis,* is listed as near threatened. Three of these species, *Avicennia bicolor*, *Mora oleifera,* and *Tabebuia palustris,* all listed as vulnerable, are rare or uncommon species only known from the Pacific coast of Central America.
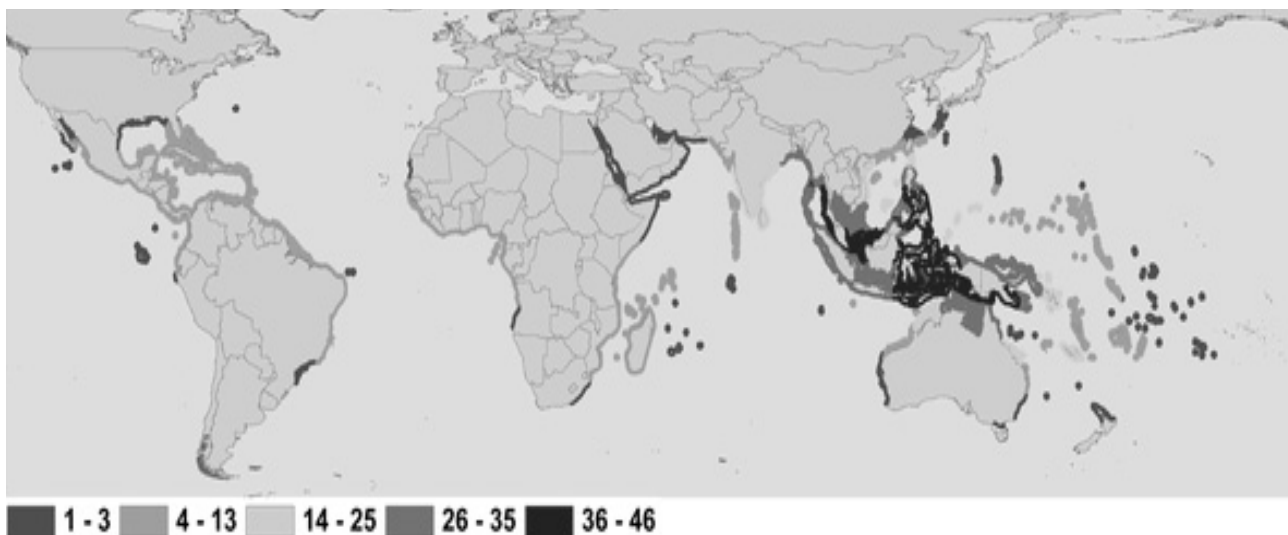

Fig. 1. Mangrove Species Richness: Native distributions of mangrove species (Source: doi:info:doi/10.1371/journal.pone. 0010095.g001).
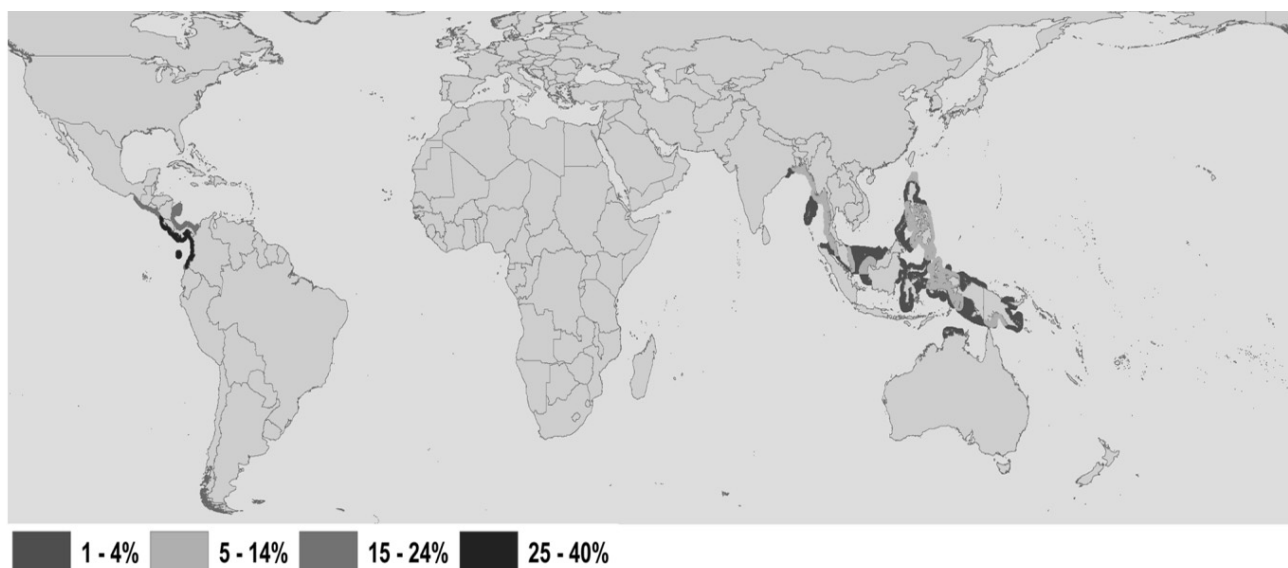

Fig. 2. Proportion of threatened (critically endangered, endangered, and vulnerable) mangrove species (Source: doi:10.1371/journal.pone.0010095.g002).

Extensive clearing of mangroves for settlement, agriculture and shrimp ponds are the major causes of mangrove decline in Latin America [11], even though there is little compensating economic return from conversion of mangrove areas to agriculture [12].

After the Indo-Malay Philippine Archipelago, the Caribbean region has the second highest mangrove area loss relative to other global regions, with approximately 24% of mangrove area lost over the past quarter-century [6]. Several surveys of Caribbean mangroves report significant regional declines due to a myriad of threats, including coastal development, upland runoff of pollutants, sewage, and sediments, petroleum pollution, storms and hurricanes, solid waste, small-scale extraction for fuel wood and minor clear cutting, conversion to aquaculture, conversion to landfills, conversion for terrestrial agriculture, tourism (involving construction of boardwalks and moorings, as well as boat wakes), and prospecting for pharmaceuticals [7, 13]. However, with the exception of the Central American endemic *Pelliciera rhizophorae* listed as vulnerable, the other eight mangrove species present in the Caribbean region did not qualify for a threatened category because they are relatively widespread and found in other regions such as West Africa or Brazil. After Indonesia, Australia, and Mexico, Brazil has the fourth largest area of mangroves, and although some areas are affected by aquaculture, human settlement and water pollution, there has been very little estimated mangrove area loss in Brazil since 1980 [6]. Mangrove diversity is naturally low at the northern and southern extremities of mangrove global range, such as southern Brazil, the Arabian Peninsula, and the northern and southern Atlantic coasts of Africa, as well as on islands in the South Pacific and the Eastern Tropical Pacific [14]. Although the majority of species present at these extremes of mangrove global distribution have widespread global ranges, and have not been listed in threatened categories, populations are more at risk from area declines at these extremes of their distribution where mangrove diversity is lowest [8].

With almost half (44%) of the world's population living within 150 km of a coastline, heavily populated coastal zones have spurred the widespread clearing of mangroves for coastal development, aquaculture, or resource use [15]. At least 40% of the animal species that are restricted to mangrove habitat and have previously been assessed under IUCN Categories and Criteria are at elevated risk of extinction due to extensive habitat loss [16]. It is estimated that 26% of mangrove forests worldwide are degraded due to over-exploitation for fuel wood and timber production [17]. Similarly, clearing of mangroves for shrimp culture contributes approximately 38% of global mangrove loss, with other aquaculture accounting for another 14% [18]. Globally, between 20% and 35% of mangrove area has been lost since approximately 1980 [6, 17, 19], and mangrove areas are disappearing at the rate of approximately 1% per year [6, 19], with other estimates as high as 2-8% per year [20]. These rates may be as high as or higher than rates of losses of upland tropical wet forests [17], and current exploitation rates are expected to continue unless mangrove forests are protected as a valuable resource [5].

Given their accelerating rate of loss, mangrove forests may at least functionally disappear in as little as 100 years [3]. The loss of individual mangrove species is also of great concern, especially as even pristine mangrove areas are species-poor compared with other tropical plant ecosystems [5]. However, there is very little known about the effects of either widespread or localized mangrove area loss on individual mangrove species or populations. Additionally, the identification and implementation of conservation priorities for mangroves has largely been conducted in the absence of comprehensive species-specific information, as species-specific data have not been collated or synthesized. Species information, including the presence of threatened species, is important for refining conservation priorities, such as the designation of critical habitat, no-take zones, or marine protected areas, or to inform policies that regulate resource extraction or coastal development. For the first time, systematic species-specific data have been collated and used to determine the probability of extinction for all 70 known species of mangroves under the Categories and Criteria of the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species.

Around 1980, the total mangrove area in Southeast Asia totaled 6.8 mil. ha, which is about 34-42% of the world's total. However, by 1990 the area had dropped to less than 5.7 mil. ha, representing a decrease of about 15%, or more than 110,000 ha per year. In 1990-2000 the annual loss had decreased to 79,000 ha; however, as the total area had also decreased, there was still a 13.8% decline in mangrove area during this decade. The largest areas of mangrove in Southeast Asia are found in Indonesia (almost 60% of Southeast Asia's total), with Malaysia ranking second (11.7%), followed by Myanmar (8.8%), Papua New Guinea (8.7%), and Thailand (5.0%) [21]. Fig. 3 shows Southeast Asian mangrove areas. Since the 1980s the number of biomass studies in mangrove forests has been increasing due to deforestation issues and the importance of mitigating tsunami and climate change. Aboveground biomass of more than 300 t/ha was reported in the mangrove forests in Indonesia [22], while in Malaysia, the highest aboveground biomass, 460 t/ha, was found in a forest dominated by *R. apiculataa* [23]. The aboveground biomass in most secondary forests or concession areas was less than 100 t/ha. The lowest aboveground biomass reported was 40.7 t/ha, for a *Rhizophora apiculata* forest in East Sumatera, Indonesia [24].

The Malaysian Mangroves: Current State, Concerns, and Ecology

In Malaysia, mangrove forests, which are under the jurisdiction of the various State Forest departments, cover an area of about 577,500 ha, with Sabah having the most extensive coverage of mangroves, accounting for 59% (or 341,000 ha) of the country's total, whereas Sarawak has 132,000 ha (23%) and Peninsular Malaysia 104,200 ha (18%). Although mangrove forests are decreasing globally, Malaysia's mangroves are generally still intact under a mangrove forest management precise system hierarchy
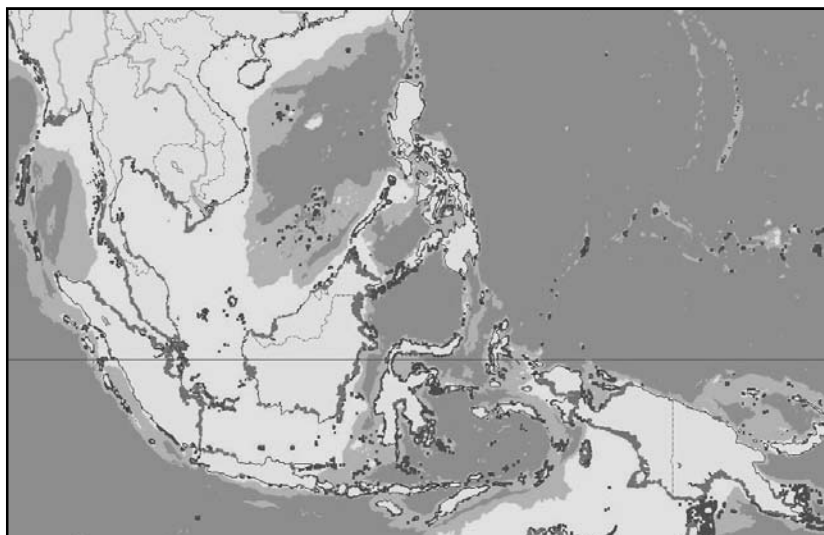
Fig. 3. Map of Southeast Asian mangrove areas (mangroves are indicated in black, coral reefs in darker black).

analysis [25]. Nevertheless, some areas of mangrove forest reserves have decreased at an alarming rate of 12% between 1980 and 1990, mostly through loss of forest to agriculture, urban development, shrimp pond farming, and deforestation [26]. Some 20% of the total has been lost through cutting for the woodchip industry in the last 40 years. Another 20% has been earmarked for possible aquaculture development in Peninsular Malaysia [27].

With over 60 different tree species, Malaysia's mangroves are extremely diverse and invaluable. Over half of Malaysia's 0.5 mil. ha of mangrove forests are concentrated in Sabah. The other major portions hug the central shores of Sarawak, while smaller parcels covet numerous lagoons and islands around Peninsula Malaysia. Mangrove forests in Peninsular Malaysia are found mainly on the sheltered coasts, estuaries, rivers and some near-shore islands. Most notable are the mangroves in the Matang Mangrove Forest Reserve along the coast of Perak. Sustainably managed for over 100 years, this dynamic ecosystem generates timber for charcoal products and harbors flourishing fishery commerce. Mangroves ascend out of the muck and mudflats of estuarine deltas. Mature stands usually comprise 20-30 species of mangrove trees found mainly on the marine alluvium along sheltered coasts and estuaries in Sabah, Sarawak, and Peninsular Malaysia.

The Malaysian mangrove zoning species-specific belts depending on soil and inundation patterns are dominated by certain key mangrove tree species with simple structures in three zones, namely *Avicennia-Sonneratia*, *Bruguiera-Rhizophora,* and the back mangrove zones. On the seaward edge, the *Avicennia-Sonneratia* species tolerate the soft soils loosened by daily tidal flooding and bury massive root systems just below the mud. These submerged structures have numerous air pockets for breathing and also send roots downward for anchorage and upward for absorption. To aid in regeneration, protruding lobes encompass *Sonneratia* fruits, thus allowing them to float atop the water currents. Meanwhile, sited on slightly higher ground, the *Bruguiera-Rhizophora* zone endures flooding only at high tide on

more compressed soils. These mangrove trees are the most valuable for timbers. The zone is recognized by its height evenness and sprawling network of aerial (but eerie-looking) root system. The elongated seedlings of *Rhizophora* hang like slender cigars, each one poised to drop off into the silty soil to start life anew. On the other hand, the clay content increases in the compact soils of the back mangrove zone. Mound-building crabs and lobsters raise the ground level another metre or so, where a thick understorey emerges from clusters of large ferns. Beyond the tidal reach are the two types of swamp palm (nipah – *Nypa fructicans* and nibong – *Oncosperma horrida*) forests flourish in brackish waters, where the dominant nipa palm, with its large feathery fronds, grows in contiguous thickets on riverbanks. *Nypa fructicans* is a general utility species providing local products such as housing thatch, cigarette paper, sugar, alcohol, vinegar, and salt. This species frequently occurs in pure stands, while nibong occurs in the drier zone of the mangrove forest. The habitat is soft, silty and shallow, coupled with the endless ebb and flow of water providing very little support for most mangrove plants, which have aerial or prop roots (known as pneumatrophores, or respiratory roots) and buttressed trunks. Tree height ranges between 7-25 m. Mangrove trees have specific characteristics such as tough root systems, special bark and leaf structures, and other unique adaptations to enable them to survive in their habitat's harsh conditions. Local people use wood from mangroves for building materials, for fish traps, and for firewood and charcoal.

Mangrove ecosystems are self-maintaining coastal landscape units that are responsive to long-term geomorphological processes and to continuous interactions with contiguous ecosystems in the regional mosaic. They are open systems with respect to both energy and matter and thus can be considered 'interface' ecosystem coupling upland terrestrial and coastal estuarine ecosystems. The fact that mangrove ecosystems are open presents us with difficult problems in terms of management and conservation, particularly with respect to estuarine-dependent fisheries.

There is no precise boundary to distinguish mangroves from the upstream and downstream ecosystems upon which they are dependent due to the collective ignorance of ecosystem functioning and the spatial organization of ecosystems in a regional setting [28]. The basic ecological research on mangroves is extensive, but almost none has examined the ecology of small-scale wood cutting in these forests. The bio-ecological and ethnographic methods were integrated to examine local wood use and cutting of mangrove forests in two areas of the Philippines [29]. The findings revealed considerable site variation in cutting intensity, with heavier cutting typically closer to settlements and in forest stands that are not effectively regulated by government or private interests. Overall, cutting is responsible for almost 90% of stem mortality in both natural and plantation forests. Mangrove management and conservation efforts can be made more effective by better understanding how local people are harvesting wood resources from these forests.

All plant roots need oxygen to survive. The soft sediments in which mangroves grow, however, are frequently low in oxygen. To cope with this, most mangroves have developed aerial roots (pneumatophores) that rise above the surface of the mud. These take in oxygen, which is then transported to the deeper roots, where water and nutrients are absorbed. The shapes of the aerial roots vary enormously, but the three most conspicuous types are pencil roots (found in *Avicenna* species), knee roots (found in *Bruguiera* sp.), and stilt roots (found in *Rhizophora* sp.). The true root systems of mangrove trees are shallow, extending less than 2 m below the mud surface, but they spread horizontally in a dense mass over large distances. Many mangrove species have a greater proportion of plant material below the surface than above, a feature that helps them to remain anchored in the soft mud and sand. Mangrove forests support a diverse range of animals and plants and are important breeding grounds for a vast array of organisms. The importance of mangrove forests in providing invaluable goods and services both in economics and environmental terms are well understood and documented. Forestry Department Peninsular Malaysia (FDPM) has been keeping abreast with current issues at the national, regional and international levels in managing the mangrove forests. FDPM has always been fully committed to the implementation of sustainable forest management practices and in line with current concerns such as climate change, conservation of biological diversity, and natural calamities (including tsunami), which has brought about a heightened expectation to the forestry profession. The policy and management of mangrove forests have great impacts on the political, social, economic, ecological, and environmental well-being of the country, and thus managing mangrove forests is very challenging to the department. The mangrove forest management system has undergone changes from merely managing for its wood produce, to a management system that incorporates multiple roles: protection and conservation. Systematic management of mangrove forests started as early as 1904, with the adoption of the first working plan for mangrove forests in Matang [30].

Despite its smelly reputation, a mangrove forest is a very dynamic and highly productive ecosystem. It not only plays multiple ecological functions essential to its surrounding habitats, but is also an important resource for coastal communities and eco-tourism [31]. Mangrove ecosystems are important nursery grounds for numerous fish and invertebrate species, including commercially valuable shrimp, crabs, lobsters, groupers, snappers, and mackerel. Many smaller, non-commercial species spend their juvenile stages in the mangroves and later migrate to the open ocean, where they become an important food source for larger commercially valuable fish. Some crabs and shrimps that spend most of their adult lives in the mangroves migrate to the open sea to spawn. Many species of algae can be found growing on and near the roots of mangroves. Sponges, oysters, barnacles, corals, bryozoans, tunicates, and other invertebrates also make the submerged mangrove roots their home. Other creatures associated with mangrove ecosystems include sea turtles, crocodiles, manatees, and dugongs. In addition to aquatic organisms, terrestrial animals including deer, raccoons, snakes, and birds utilize the mangrove habitat as their home and hunting grounds. Mangroves and adjacent seagrass beds and coral reefs are linked by the water masses that exchange between them with the tide, and by the animals and plants that move with the water between these habitats. The water flow link also is important for the transport of nutrients between these different coastal habitats, though the importance of the nutrient exchange between the habitats depends on their proximity. People living in tropical coastal zones have long utilized mangroves for a variety of purposes. In addition to the use of the habitat for fishing, various products from the trees are valuable resources. The propagules of some species, for example, are eaten. Some people use the bark as a source of tannins or dye, and the wood to build durable and water resistant houses, boats, pilings, or furniture. Black mangrove wood and the wood from the closely related Buttonwood tree are used to produce charcoal. Even the leaves are used, in teas, medicines, food for livestock, or smoked like tobacco, and the flowers are in some localities important for bee farmers in the honey industry. Utilization of the renewable natural resources of mangroves in general enhances their perceived value to the people who use them. It also is well recognized by people living in coastal regions that mangroves are a flexible soft buffer to the waves generated by tropical storms. They therefore provide protection for the adjacent terrestrial environment. It is an unfortunate fact that in many places mangroves are not protected from coastal development and that construction projects destroy them to build houses, farms, roads, airports, and golf courses. As a result, large tracts of habitat have been lost, at great cost in the past century.

Mangrove forests are important because they protect coastlines against erosive wave action and strong coastal winds, and serve as natural barriers against tsunamis and torrential storms. They prevent salt water from intruding into rivers, and they retain concentrates and recycle nutrients and remove toxicants through a natural filtering process. The mangroves can provide resources for coastal communities who depend on the plants for timber, fuel,

food, medicinal herbs and other forest products. It can be harvested sustainably for wood and other products. Mangroves are an important breeding ground for many fish, crabs, prawns, and other marine animals, essential for sustaining a viable fishing industry. Malaysia's mangroves are more diverse than those in tropical Australia, the Red Sea, tropical Africa and the Americas. About 50% of fish landings on the west coast of Peninsular Malaysia are associated with mangroves. These coastal forests also harbor an abundant array of invertebrate animals – crabs, oysters, mollusks, and crustaceans – that provide food for aquatic and human life. Long bands of mangrove forest act as buffers against penetrating storms and protect coastlines from the pounding sea. And the nutrient-rich waters and organic muddy soils provide healthy habitats for marine species, such as shellfish and cockles, and furnish breeding grounds for many fish, prawn, and shrimp species [32]. Mangrove habitats also provide shelter and food for other animals. Some, like the proboscis monkey of Borneo, are of particular importance because of their endangered animal status. Even migratory birds – from faraway lands – such as the Bar-tailed godwit descend on Malaysia's mangrove swamps to take temporary refuge and 'refuel'. And monkeys and snakes live in mangroves as part of the wild menagerie.

It is an obligation by the relevant authorities, especially the State Forestry Department, to ensure that the rate of seedling survival in the afforestation and reforestation activities is successfully monitored, mapped, and quantified. One of the most efficient techniques available is the use of geospatial information technology consisting of geographical information systems (GIS), global positioning systems (GPS), and remote sensing (RS). Using this technology and integrating the different thematic maps that show environmental conditions of a specific region, and suitable and potential positioning of different species for plantation and rehabilitation programs could be well determined and monitored [33]. For mapping and detection of individual mangrove species for reforestation and afforestation purposes, mathematical functions such as Boolean logic, fuzzy logic, and neural network can easily be applied. It is expected that suitable species-site matching for reforestation and afforestation of mangroves could be implemented with such geospatial tools [33]. The need for high resolution maps in the management of tropical environments is increasing and emphasized by the rapid anthropogenic development often occurring in coastal zones [34]. In areas subject to humid tropical climate, such as the West Indies, cloud coverage often disturbs image acquisition by orbital imagery. Moreover, as these tropical coastal ecosystems (i.e. coral reefs, mangroves, and seagrass beds) are intricate and geographically complex, high resolution data must be used to accurately restore these features. Digitized aerial photographs meet these requirements by providing higher resolution.

Ecological Management of Mangrove Forests in Peninsular Malaysia

Mangrove forests' ecological management system has undergone changes from merely managing for its wood produce to a management system that incorporates multiple roles, protection, and conservation. Systematic ecological management of the Malaysian mangrove forests started as early as 1904, with the adoption of the first working plan for mangrove forests in Matang, Perak. The Matang mangrove is identified as the best described managed mangrove forest in the world and is an example of sustainably ecologically managed mangrove forests. The Matang mangrove is still intact, providing various goods and services, sustainably. This is itself is a manifestation of the successful ecological forest management practices that aptly earned Matang mangroves the reputation as the best managed mangrove forest in the world. Special emphasis to the protection of mangrove forests is duly recognized and given specific attention in the National Forestry Act 1984, and further enshrined in the National Forest Policy 1978 (revised 1992). Future ecological management of mangrove forests in Peninsular Malaysia will adopt an integrated approach by adopting further refinement to the current management approach and incorporating the latest findings and updated information through more vigorous research and development (R&D), scientific expeditions, and ecological studies on mangrove forests. The National Forestry Policy and other policies related to mangrove forests need to be revised from time to time to match prevailing conditions and requirements, to ensure the realization of its multiple functions in perpetuity.

Conservation, Replanting, and Restoration of Mangroves

The planting of mangroves along coastlines damaged by cyclones and tidal bores occurs in countries such as Vietnam, China, and Bangladesh. In Bangladesh, 120,000 ha of mangroves have been planted since 1966 [35]. Nowhere else have mangroves been planted on such a large scale. In this case the mangroves were planted on newly accreted land. Two species of mangrove, *Sonneratia apetala* and *Avicenniao ficinalis*, dominate the mangrove plantations, usually as mono specific stands. Meanwhile, in Pakistan mangrove conservation in Sonmiani Bay was successful through community-based participation [36]. The planting of mangroves has been highly successful in protecting and stabilizing coastal areas and in providing substantial timber production. Such artificially constructed mangrove forests seem highly beneficial but little attempt has been made to study their ecology.

Two approaches can be used in the planting of degraded mangrove areas: natural and artificial regenerations. In natural regeneration, it uses naturally occurring propagules or seeds of mangroves as the source for regeneration. The mix of species regenerated is regulated by the species that occur locally. There are several advantages in natural regeneration, but the prime one is that the resulting forest is likely to be more akin to the original mangrove vegetation, unless there has been severe imposed selection of available propagules. Other advantages of natural regeneration are that it is cheap to establish, less labor is required, less soil disturbance results and the seedlings establish more vigorously.

If this technique is employed it is essential that there be an adequate supply of seeds or propagules, and this is usually achieved by ensuring that a number of seed-bearing trees are present in the area. It has been advocated that, for *Rhizophora* stands, the number of seed-bearing trees should be about 12 trees/ha [37]. Apart from a lack of seeds and propagules, poor natural regeneration may be due to weed competition, excessive amounts of debris, poor soil conditions, or disturbed hydrodynamics of the site. Natural regeneration of mangroves should be the first choice of any rehabilitation program, unless there is irrefutable evidence that it will be unsuccessful.

Meanwhile, the artificial regeneration involves planting of seeds, propagules, or seedlings in areas where there is insufficient natural regeneration. One technique is to transplant seedlings (wildings) to a new location. Another technique is to collect ripe seeds or propagules and to plant them directly into the site. An alternative is to raise seedlings, or small trees, under nursery conditions and then to transplant them to the field. It is clearly cheaper to collect seeds and propagules and to plant them directly, but there are conditions where it may be difficult to achieve regeneration by this method, such as a paucity of available propagules. Such adverse conditions may warrant the use of nursery-raised seedlings. It is not, however, normally the method of choice. There are advantages to artificial regeneration: the species composition and the distribution of seedlings can be controlled; genetically improved stock can be introduced; difficult or pest-infested sites can be more easily restored.

The selection of mangroves to be planted is generally determined by three factors in decreasing order of importance: the mangrove species occurring naturally in the locality of the afforestation site; the availability of seeds or propagules; and the objective of the planting program. The zone in which the mangroves should be planted, such as seaward, middle or landward or riverine upstream or downstream can be determined by observation of the common mangrove species occurring naturally in local sites. Similar observations will determine the soil type required and the best tidal inundation regime. It is important that individual species should be planted within their specific tidal and flooding range. In practice, it is often efficacious to plant initially small patches of mixed mangrove species in soil that has been specially prepared. In this way the afforestation process can be given the best chance of success. It is interesting to note that the number of species that have been planted in rehabilitation projects represent only about thirty percent of the total number of mangrove species that are known to exist. Details of planting procedures in various rehabilitation and afforestation projects around the world and a summary of the pests that can be encountered have been well reported [26, 38]. The data on the area of mangroves planted are mainly based on a number of local reports and personal knowledge. Such figures should be taken as being only indicative. It would be necessary to have much more refined data if the scale of rehabilitation activities is to be fully analyzed. Of the 90 or so countries around the world that contain mangrove vegetation, only some 20 have attempted any form of mangrove replanting.

Only nine of these 20 countries have planted more than 10 km since 1970. Bangladesh, Indonesia, the Philippines, and Vietnam stand out as countries that have put the most effort into the rehabilitation of mangrove ecosystems. In the case of Bangladesh, most of the planting has been in the form of afforestation on newly accreted land. In Indonesia and the Philippines, the plantings have been on degraded areas caused by clear felling, shrimp ponds, and population pressure. In Vietnam, the causes are similar but have been compounded by the devastating effects of recent wars.

Apart from national governments, numerous international organizations have supported or are supporting mangrove replanting programs. Included in this list are the European Union, the World Bank, the Asian Development Bank, the World Wide Fund for Nature (WWF), the International Union for the Conservation of Nature (IUCN), the Food and Agricultural Organization (FAO), UNESCO, UNEP, UNEP, Wetlands International, the International Tropical Timber Organization (ITTO), the Save the Children fund, and the Australian Centre for International Agricultural Re-search (ACIAR). This list is no doubt incomplete but it reflects personal knowledge of their activities.

In an attempt to get an overview of the work being undertaken internationally in the sphere of mangrove rehabilitation, several of these organizations were approached for information and, if possible, copies of relevant reports so that some evaluation of the scale and success of such programs could be undertaken. The response was almost complete silence. One of the challenges is to gauge how successful rehabilitation projects have been and what lessons have been learned from failure. It is clearly impossible to carry out such a critical review without access to the myriad reports that must be hidden in the archives of the many sponsoring agencies. One is left with the impression that there are several reasons for this dearth of information. They include bureaucratic sloth, proprietary reluctance to reveal important findings, inadequate dissemination mechanisms, and a myopic view of the general importance of rehabilitation programs. The result is that there are many mangrove rehabilitation programs being carried out without any reference to lessons that might be learned from other, similar programs. One must suspect a great duplication of effort. In addition, there is probably very little external critical analysis of the worth of many of the projects and few of the results are ever published in refereed journals. There is a real need for an archival system to be established where reports on mangrove rehabilitation can be lodged and accessed easily by interested people. The Internet may offer a partial solution. However, a more organized system needs to be established by one of the international agencies, in concert with other agencies, as it would require considerable resources to establish and maintain it. Experience dictates that such co-operation will remain elusive.

Conservation of mangroves can be enhanced by gazetting all remaining mangrove forests within forest reserves or protected areas. Calls for mangrove conservation and restoration gained popularity following the deadly tsunami catastrophe that struck the Indian Ocean near

Bandar Acheh, Sumatera, in December 2004. Some mangrove forests are already gazetted, such as Matang Forest Reserve in Perak, Kuala Selangor Nature Park in Selangor, Bako National Park in Sarawak, Kota Kinabalu City Bird Sanctuary, and Sepilok Forest Reserve in Sabah. But many other mangrove areas are still without any protection. It is important that well-balanced coastal land-use plans, such as maintaining sustainable limits in logging and other harvesting activities of its resources, be devised. This is needed to retain the protective mangrove buffers along coastlines and rivers to prevent erosion and natural disasters, such as tsunamis. In addition, managing mangrove forests as fishery reserves would encourage environmentally-sensitive commercial aquaculture activities, in particular to raising public awareness and educating the community to discourage indiscriminate clearing.

Another management conservation aspect is the introduction of social forestry schemes so as to rehabilitate the damaged mangrove forest areas by planting and managing for small-scale village timber enterprises. Mangrove species like *Rhizophora mucronata* or *R. apiculata* are particularly ideal for mangrove plantations as they are both fast growing and lucrative. As for Sabah, of the 341,000 ha of mangrove forests, 93% or 317,423 ha are classified as permanent forest reserve (Class V) under the 1968 Forest Enactment. For the past three decades the Sabah Forestry Department (SFD) considered mangrove forests as conservation forests with limited utilization such as sustainable production for pilling poles, charcoal, and fuel-wood for domestic consumption. Although 45% of mangrove forests in Sabah have been exploited for their timber in the past, approximately 40% of these disturbed mangrove forests have regenerated naturally [39]. Another 15% of mangrove areas (due to mangrove clearance for shrimp pond farming, aquaculture, etc.) need to be replanted/restored [40]. Apart from small-scale extraction of mangroves for charcoal and piling poles production and mangrove clearance (for shrimp pond farming and oil palm cultivation), there is relatively little demand for mangrove timber in Sabah today. Mangroves in Sabah are now valued more for the protection they provide against coastal erosion, the habitat for all sorts of marine life, and also for their general biodiversity conservation function. Despite the functional importance of mangrove ecosystems, their habitats are under threat due to conflict of interest on their usage. In Sabah, the Forestry Department, through the Forest Resource Division (FRM), focuses its restoration programs on mangrove reserves along the coastal areas throughout Sabah such as Sandakan, Semporna, Kunak, Lahad Datu, Kota Kinabalu (Putatan and Tuaran), Kota Belud, Tawau, and Beluran districts.

It was observed that the main obstacle for restoration at Putatan was the occurrences of strong currents and also sand accumulation along the beach, whereas in Meruntum, a phenomenal disturbance on mangrove seedlings was by barnacles. For the first six months at Meruntum beach, the mortality rate was observed to be 10%. However, after 10 months a high mortality rate of mangrove seedlings was recorded due to the high abundance of barnacle populations. In Putatan beach almost 80% of planted mangroves (using propagules and/or seedlings) and other species were totally wiped out either by strong currents (e.g. caused by typhoon Hagibis) and/or sand accretion. Some of the issues and challenges in replanting include the frequent disturbance by crabs that can damage the young shoots of mangrove seedling. It is important to replace the damaged mangroves plants. It is also advisable to use older seedlings as planting material in the field. A barnacle attack was observed in Putatan (serious disturbance) and Lahad Datu (mild attack). In November 2007 Typhoon Hagibis also caused major damage to planting areas in Putatan. The strong current is most likely a major problem in the coastal areas of Lahad Datu, Tawau, and Semporna. It is therefore advisable to avoid large-scale planting activities in these areas. The strong current, seasonal green algae, and garbage waste were the major problems in Kg. Hampilan, Kunak. Replacement planting had to be carried out immediately. Given the rising cost of the mangrove restoration program, it is suggested that additional allocation from the Federal Government is required in order to support the increasing cost of mangrove restoration. Moreover, an additional allocation also is needed for the implementation of research, promoting environmental education and also promoting the practice of sustainable forest management with respect to nature and services that mangrove ecosystems provide to humanity.

Forest Engineering for Best Ecological Management Practices

Great potential exists to reverse the loss of mangrove forests in Malaysia and worldwide through the application of best management practices (BMPs) and principles of ecological forest engineering approaches, including careful cost evaluations prior to design and construction. Previous documented attempts to restore, where successful, have largely concentrated on creation of plantations of mangroves consisting of just a few species, and targeted for harvesting as wood products, or temporarily used to collect eroded soil and raise intertidal areas to usable terrestrial agricultural uses. The importance of assessing the existing hydrology of natural extant mangrove ecosystems, and applying this knowledge to protect existing mangroves and achieve successful and cost-effective ecological restoration, if needed, have been well documented [41]. Previous research also has documented the general principle that mangrove forests worldwide exist largely in a raised and sloped platform above mean sea level, and are inundated at approximately 30% or less of the time by tidal waters. More frequent flooding causes stress and death of these tree species. Prevention of such damage requires the application of some understanding of basic mangrove hydrologic and oceanographic principles in forest engineering.

Rehabilitation of a Mangrove Ecosystem

In order to consider the rehabilitation of mangrove ecosystems it is necessary to define the term clearly. In the present context, rehabilitation of an ecosystem can be

defined as the act of partially or, more rarely, fully replacing structural or functional characteristics of an ecosystem that have been diminished or lost, or the substitution of alternative qualities or characteristics than those originally present with provision that they have more social, economic or ecological value than existed in the disturbed or degraded state. Likewise it has been agreed that restoration of an ecosystem is the act of bringing an ecosystem back into, as nearly as possible, its original condition [38].

The need for rehabilitation of a mangrove ecosystem implies that the area under consideration has been altered or degraded in a way that conflicts with defined management or conservation objectives. Hence, rehabilitation is often the result of competition for land use, though at times it can arise because of climatic impacts that have destroyed the natural vegetation. It is essential that goals be defined as a first step in the rehabilitation process. These are normally linked to specific activities or combinations of activities. Goals determine the rehabilitation process and help identify the elements that must be included to provide the project with a clear framework for operation and implementation. The establishment of criteria for the success of the rehabilitation process must be a priority.

A prime task is to ascertain whether the mangrove ecosystem needs to be rehabilitated or, indeed, if it can be rehabilitated. A number of factors may influence the similarity of the rehabilitated mangrove ecosystem with any mangrove ecosystem that may have previously occupied the site. These include genetic changes in the populations, natural variability of the mangrove eco-system, topographical and hydrological changes to the site, local climatic changes, changes to neighboring ecosystems, and the goals of the rehabilitation program. Mangrove ecosystems are very dynamic and their growth and decline often reflect the changing conditions of the coastal environment in which they grow. Any attempt to restore the structure and function of mangrove forests may prove elusive and impractical. This contention is supported by consideration of old growth forests. Such forests have peculiar ecological characteristics that disappear when the forests are logged and converted to younger states. In some parts of the United States old-growth has become a criteria for the preservation of the forests. It has been argued that no single stand of mangroves will have all the characteristics of old-growth and even when many of the characteristics are present it does not assure that the stand is old-growth [42].

Whether a mangrove stand reaches an old-growth stage depends on the dynamics of the coastal system under which it grows. Sea-level changes, hurricanes, frost, lightning, fires, and anthropogenic disturbances all can alter mangrove growth. It is concluded that old-growth mangrove stands are an improbable state and that they can revert to younger stages. There are three main criteria for judging the success of a mangrove rehabilitation program: the effectiveness of the planting (the closeness to which the new mangrove ecosystem meets the original goals of the rehabilitation program), the rate of recruitment of flora and fauna (a measure of how quickly the rehabilitated site recovers its integrity), and the efficiency of rehabilitation (which can be measured in terms of the amount of labor, resources and material that were used). In the case of mangrove ecosystem rehabilitation, the effectiveness and efficiency are only sometimes quantified and the recruitment of flora and fauna rarely quantified.

The three main reasons for mangrove ecosystem rehabilitation are: conservation of a natural system and landscaping, sustainable production of natural resources, and protection of coastal areas. The degree to which the original ecosystem is rehabilitated may vary in each case. If a degraded mangrove ecosystem is being rehabilitated for conservation or landscaping purposes, most ecological processes must be maintained and as much genetic diversity preserved as possible. However, there are few examples of mangroves being rehabilitated for the sole purpose of recreating a conservation or landscaped area. There are also examples of mangrove planting following damage from an oil spill that constitutes afforestation for conservation purposes [43]. In mangrove rehabilitation of this type the subsequent level of practical management is often very low and quantification of the success of the rehabilitation rarely goes much beyond assessment of the growth of the trees. The most common method of conserving mangrove ecosystems is by the creation of protected areas in un-disturbed sites. This is usually achieved through the establishment of nature reserves, national parks, wildlife sanctuaries and internationally protected sites. The conservation of biological diversity is central to dogma of the international conservation community.

It is perceived as pivotal to nature conservation as species extinction threatens not only the idealized Western view of nature but depletes the genetic resources that are essential for continued human prosperity [44]. However, it is interesting to note that the relationship between changes in biodiversity and eco-system function is not easily quantified in mangrove ecosystems despite the extensive pool of information [45]. In addition, the value of focusing the purpose of nature conservation on biodiversity can be queried. It has been questioned why bio-diversity, a term that they see as jargon, should be paramount in the thinking of conservationists, and they argue that conservation should be more inclusive of community participation [44]. They believe that nature conservation practices should stand within the context of multiple land use. They argue that the conservation of ecological processes to maintain arboreal habitat, water, and the fertility of soil may better integrate nature conservation into other land uses. As examples of the flexibility of approach that can be built into conservation programs, two examples of mangrove conservation in Indonesia were cited [44].

In one area, Pantai Timur Mangrove Nature Reserve, they argue that the integration of human use and opportunities for social and economic development is appropriate. In the other, Bunaken National Park, they argue (for sound ecological reasons) that people and development activities should be excluded. They also maintain that the accommodation and maintenance of ecological processes should be an over-riding factor in achieving sustainable conservation management: not just a species focus. This approach con-

fronts the rigidity of restoration ecology multiple use systems for high and sustainable-yield mangrove ecosystems managed as multiple use systems for the high and sustainable yield of natural products. This implies careful management and perturbation of the ecosystem without loss of productivity. Rehabilitation only becomes necessary where the mangrove land has been degraded or affected by the utilization of the land. Examples of the use of mangrove ecosystems for sustainable yield of natural products are timber and charcoal [46], and shrimp production [47]. Unfortunately, many of the attempts to utilize mangrove ecosystems in this way have ended in disaster as a result of poor, short-term, and greedy management practices.

However, this should not lead to the conclusion that mangrove ecosystems cannot be managed to deliver high yields of natural products on a sustainable basis. Much of the opposition to using mangrove ecosystems for the yield of natural products stems from the belief that the survival of the ecosystem will inevitably be compromised. Even without any disturbance by people, mangroves are dynamic systems and tend to decline and flourish as a result of slight changes in the natural environment. If a mangrove forest is disturbed by logging, it is unlikely that the forest will be regenerated, either naturally or artificially, to something like its original state, as the mix of species, soil type, density of trees, and numbers of animals will almost certainly change. However, this does not mean that the modified ecosystem is not sustainable. It does mean that a different ecosystem may emerge, which will mean a high sustainable yield of natural products. This will help meet the demands of people unable to maintain a living today and of the many more such people that will exist in the future. Sustainable production of natural products seeks to avoid environmental disasters in the short and long terms and to encourage preservation of the natural system as much as possible. In such endeavors involving a mangrove ecosystem there are conflicting goals to be considered. These include the preservation of environmental integrity, economic efficiency, and equity for the local community. The approach to rehabilitation in such cases is essentially that of classical land management, with forestry or animal husbandry of a specialized kind based on the understanding of the ecology of the natural system.

The necessary requirement is knowledge of the processes essential to developing and supporting the productivity of the system as a whole, rather than its parts. If there is to be intensive and selective use of mangrove forests, then specialist knowledge needs to be acquired for plants and animals in areas such as genetics, nutrition, stocking procedures, disease control, and harvesting. In turn, this knowledge needs to be supported by appropriate technology and suitable legislation. This type of rehabilitation often has the goal of restoring the productivity of the land without undue regard to how the restored ecosystem compares with the original one. The main objective is to increase primary productivity. This may involve activities such as reducing environmental stress, adding material, and changing site conditions. These can be expensive processes. Some of the problems that can arise in these programs can be illustrated by

reference to a project concerned with community participation in mangrove forest management and rehabilitation in Southern Thailand [48]. Problems include major differences between the sponsors of the project and the supervisors of the project, such as expatriate advisors and local academics and villagers; lack of motivation among the local community; lack of intra-and inter-agency collaboration; conflicts and inequity within the local community and impacts from major development projects not foreseen at the commencement of the program. The identification of such problems is a healthy sign that they can be overcome, but there are important lessons to be learned from such experiences. All too often such well-meaning projects do more for the sponsors than the recipients, with not unexpected resentment among local villagers.

Two specific considerations when rehabilitating mangrove ecosystems are required, namely the site selection for mangrove planting and monitoring, and maintenance of rehabilitated mangrove ecosystems. It is difficult to generalize about the selection of a planting site for mangroves in a rehabilitation program as it will depend on local conditions and the mangrove species to be planted. The goals of the rehabilitation will influence site selection. An understanding of the cause of the initial degradation of the chosen site is essential, as this may require a remedy. Generally, mangrove forests are best developed on low energy muddy shorelines, where there is an extensive suitable intertidal zone with an abundant supply of fine grain sediment. Essential characteristics are that the soil, whether it is sandy, muddy or clayey, must be stable and non-eroding and of sufficient depth to support planting. Some amount of sedimentation on the site may help stabilize the seedlings, but excessive sedimentation may affect all growth. The rate of sedimentation is an important factor to measure. The topography of the site is critical in determining the success of the rehabilitation project and some degree of gentle slope is essential for proper drainage.

The hydrology of the site also is of great importance as it controls the quantity, quality and timing of water entering the site. It is vital that young plants are inundated regularly by the tide but not to the extent that they are drowned. This means selecting a relatively shallow region where the plants are exposed to the air for reasonable periods of time. Intertidal position can be of great importance for the survival of mangrove seedlings, as tide height is a critical factor in determining survival. This is because seedlings are susceptible to physical damage and are subject to physiological stress if submerged for too long. In some planting programs, sites may be graded to adjust the depth of tidal flooding prior to planting, but such preparation is rare. If the area to be rehabilitated is subject to significant wave action and erosion, then barriers can be erected to protect the site while at the same time allowing natural tidal inundation. In rehabilitating a site, it is important to consider the status of adjacent sites.

The greatest chance of success of the rehabilitation program is provided if adjacent sites are fully functional in an ecologically compatible fashion. On the other hand, if there are highly degraded areas close to the rehabilitation site

they may adversely influence the success of the rehabilitation program. It is also important that planting sites are sheltered, as young seedlings cannot withstand strong winds or force currents. Mangroves are most luxuriant in areas of high rainfall or abundant fresh water supply. The requirement for fresh water may seem strange, as mangroves are considered to be halophytes, but while some mangroves do not seem to thrive in non-saline conditions others grow well in only slightly brackish conditions. The tolerance to salinity varies widely between the mangrove species. However, salinities in the hypersaline region pose problems for all mangroves as it mirrors the condition of drought in terrestrial plants. No mangrove grows optimally under conditions of hyper salinity, though many species can survive. Mangroves are generally shallow rooted and so the physical and chemical properties of the top soil are probably more important than those at greater depth. The extent to which growth of mangroves is controlled by the presence or absence of nutrients is not at all clear [49]. The presence of seagrasses, naturally regenerating seedlings (wildlings), or scattered growth of grasses indicate that the site may be fit for afforestation.

Another factor that needs to be taken into account is whether the mangrove species to be planted is shade tolerant or not. This will determine the canopy structure of the site selected. Generally, very little preparation of the planting site is necessary, but the site must be cleared of all debris such as coconut or banana trunks, leaves, bamboo, and tree branches. However, mangrove rehabilitation is sometimes undertaken on extremely degraded sites that are the result of shrimp farming, mining, or timber harvesting, or the site may be a newly accreted mudflat. In such cases, the sites may be highly saline, extremely low in oxygen, and virtually devoid of essential chemical elements such as nitrogen and phosphorus. Also, the soil conditions may fluctuate wildly, vegetation cover may be negligible, and exposure to solar radiation may be intense. If the degraded site is a disused shrimp pond there may be accelerated soil erosion due to increased surface runoff, a decrease in soil water storage capacity, a reduction in the biodiversity of soil fauna, a depletion of soil organic matter, the presence of acid sulphate soils, and the addition of toxic chemicals. It remains to be established if disused shrimp ponds can be rehabilitated [50]. If the site is on drier marginal land, such as abandoned paddy fields, then some detailed land preparation may be required. It is likely such land will be highly acidic due to the oxidation of iron sulphides in the soil and that there may be toxic levels of aluminium in the soil. In order to remove the toxic chemicals and to re-store the natural soil condition, it is necessary to ensure that the soil is well flushed by the incoming tides and by fresh water from rain run-off. Such environmental conditions provide extremely difficult habitats, and few ecological studies can provide any assistance on how to approach planting mangroves on such sites or how to en-sure the reappearance of fauna. If the planting site is an area where mangroves have been clear-cut (usually for timber and charcoal production), then it may be infested by the *Acrostichum* fern. In such cases it is important to clear the site extensively as the presence of *Acrostichum* will inhibit the establishment of the required tree species. This procedure has proved to be difficult and expensive in Malaysia and Indonesia.

In Thailand, infestations by barnacles retarded the growth of seedlings planted on newly accreted mud. Also, attacks by crabs in degraded mangrove forests in abandoned shrimp farms and mining areas caused seedling mortality of some 10% [51]. Recent studies have shown that the consumption of mangrove propagules by crabs may greatly affect mangrove regeneration and influence the distribution of certain species across the intertidal zone [52]. In some parts of the world monkeys can also be a problem. It is therefore important to carry out some preliminary studies of the proposed site to see if predatory animals pose a significant risk. If it does, special precautions, such as encasing the seedlings in protective structures, may need to be taken when planting. A final consideration, but one that is essential for nearly all mangrove rehabilitation projects, is the involvement and support of the local community. The pressure of the local population will determine the structure and function of the mangrove ecosystem that supports them. The form of the rehabilitated site will largely depend on the activities of the local population. It must be accepted that people have the responsibility to say what sort of landscape they want to live in, now and in the future [44]. In many instances the outcome of the rehabilitation program will be determined directly by interaction with the local people and not by a desire for ecological restoration.

Once a mangrove rehabilitation program has been completed, it is essential to monitor progress and to maintain the site. These activities are similar to those that would be normally undertaken in any forestry program. Three to five years is often specified as the monitoring period in small-scale rehabilitation programs, but more realistically 10 years should be the monitoring period. For large afforestation projects up to 30 years may be necessary. If rehabilitated mangrove ecosystems are to be contrasted with naturally occurring ones, then comparative measurements of productivity, movement of organic matter and organization of the food chain will have to be carried out as well. If one is interested in monitoring the restoration of a whole mangrove ecosystem then one would have to measure the composition of species present, the structure of the plants and soil, the heterogeneity of the system, the performance of basic ecological processes, and the dynamics and resilience of the system [53]. As yet, such measurements have not been attempted in rehabilitated mangrove ecosystems.

There are many mangrove rehabilitation projects with various aims that have been undertaken in the last few years or that are currently underway [38, 54]. In the same period, there has been an explosion of scientific papers on mangrove biology and ecology. Mangrove ecologists tend to be concerned primarily with the intrinsic nature of their research rather than in initiating the use of their findings in the management of mangrove rehabilitation projects. There is a paucity of ecological studies on heavily degraded mangrove ecosystems and little attempt to extrapolate ecological findings from normally functioning mangrove ecosystems to those existing under stressed conditions.

Ecologists should not be too eager to confine their efforts solely to the provision of sound ecological advice but should be prepared to have more say in the way the advice and data are used [55]. Likewise, in a comprehensive review of studies on mangroves in Malaysia, it is recommended that more attention should be paid to management issues as they represent more critical areas of concern than purely ecological processes. There is a need for applied ecological research aimed at testing the decisions made when rehabilitating mangroves. This seldom happens. Indeed, much mangrove research is done in isolation from the needs of the managers of the rehabilitation projects. There is an urgent need to study the failures of mangrove ecosystem management. Likewise, there is a need to do research that will enhance mangrove ecosystem rehabilitation. There is a lack of innovative research programs that focus on the problems of mangrove ecosystem rehabilitation and, for that matter, on the intrinsic structure and function of mangrove ecosystems. An exception to this is the use of molecular markers in assessing polymorphism in mangrove species [56].

Issues and Threats Associated with Mangrove Conservation, Restoration and Protection

Eleven international treaties and instruments afford some protection, at least on paper, to mangroves in general, some of which have been in force for over 50 years. These treaties and instruments include the RAMSAR Convention, the Convention on the Prevention of Marine Pollution, CITES, the International Tropical Timber Agreement, the Convention for the Protection and Development of the Marine Environment of the Wider Caribbean Region, and the Convention on Biological Diversity [57, 58]. However, these treaties and instruments do not necessarily confer legal protection to mangrove ecosystems, and none of them address conservation, preservation, or management of particular mangrove species. Similarly, the current trend of global decline of mangrove areas indicates that exploitation continues unabated despite the presence of these laws and treaties [6]. As far as Malaysia is concerned, there are still many threats to Malaysian mangroves. Naturally resilient, mangrove forests have withstood severe storms and changing tides for many millennia, but they are now being devastated by modern encroachments. Urban and aquaculture wastewater discharge, oil pollution, biological invasion, and the influence of water transportation remain serious threats to mangroves in Malaysia despite the apparent success in mangrove conservation and reforestation during the last two decades. For a long period of time, wastewater from the upstream and landfill pollution discharged directly into the mangrove wetland without proper treatments that were popular in the coastlines of several states in Malaysia.

Environmental stress can kill large numbers of mangrove trees. In addition, the charcoal and timber industries also have severely impacted mangrove forests, as well as tourism and other coastal developments. Wherever mangrove forests have been cleared, the yields of coastal fish-

eries have drastically fallen. The reason is that many economically important fish species use mangroves for their reproduction. The loss of these refuges removes a life-supporting resource, not just for these fish populations but also for the coastal population. Through uncontrolled mangrove forest logging, a natural protective belt is lost. The gravest threat to the world's remaining mangroves is the rapidly expanding shrimp aquaculture industry. Since mangrove forests have been classified by many governments and industries alike as useless swamps, it has made it easier to exploit mangrove forests as cheap and unprotected sources of land and water for shrimp farming. Thousands of hectares have been cleared to make room for artificial shrimp ponds. The amount of mangrove forest destruction is alarming. The use of an area for shrimp breeding is problematic because after a maximum of 10 years' use, shrimp ponds have to be abandoned due to contamination of the pond bottoms with chemicals, over-fertilization, pesticides and antibiotics. At one time 1 ha of mangrove forest offered livelihood for about 10 families; nowadays a 500 ha shrimp-farm provides probably only five jobs. Globally, as much as 50% percent of mangrove destruction in recent years has been due to clear cutting for shrimp farms. Mangrove forests are in danger of disappearing from the coasts in the next 20 years. It has to be in the public interest to do everything possible to preserve mangroves' ecological functions.

Although the self-purification functions of mangrove wetlands have been reported [59-62], pollution still has adversely changed the ecosystem functions and the biodiversity of the mangrove ecosystem [63]. For example, the quantities and densities of benthic animals, birds, or fish have declined in several polluted mangrove forests along the coast of Perak. Biological invasion is a global problem for its great threats to native species and local ecosystems [64, 65], which is also common to the mangroves in Malaysia. The strong dispersal and reproductive capacities of the seeds or new ramets from rhizome segments of *S. alterniflora* made it a very invasive species, which has brought serious threats to the Chinese native mangroves [66].

On the other hand, there are still some great challenges in replanting mangroves on locations where mangroves have been destroyed. First, the survival rates in mangrove afforestation are quite low. Environmental factors, such as tidal inundation periods, seawater salinity and air temperature can affect the survival rate of mangrove reforestation. Selecting suitable tidal zones for mangrove replanting (i.e. the plantable tidal flats, which refer to the tidal flats where natural mangroves distributed and the planted mangrove seedlings can survive, is essential in any mangrove restoration project. Secondly, mono-species or exotic species are often used in mangrove reforestation in Malaysia, which reduces the biodiversity of replanted forests. Although it has long been known that reduced biodiversity is sensitive to be easily subjected to insect outbreak and has low ecological values, a few species of native mangroves (*Sonneratia* sp., *Rhizophora* sp.) were frequently planted in monoculture for most of the reforestation projects.

This is because most of these reforestation projects are aimed mainly for the appearance of the planted trees and for the high survival rates. On the other hand, some fast-growing exotic mangrove species have been introduced and intensively used in many mangrove afforestation projects in Malaysia during the past 10 years. However, more studies are needed to test this approach before it is implemented on a large scale.

The continued exploitation of mangroves worldwide has led to habitat loss, changes in species composition, loss of biodiversity, and shifts in dominance and survival ability. Worldwide, about half of the mangroves have been destroyed. Indian mangrove biodiversity is rather high. The increase in the biotic pressure on mangroves in India has been due mainly to land use changes and on account of multiple uses such as for fodder, fuel wood, fibre, timber, alcohol, paper, charcoal, and medicine. Along the west coast alone, almost 40% of the mangrove area has been converted to agriculture and urban development [67]. Our understanding of the natural processes in this vulnerable and fragile ecosystem is far from adequate. Environmental awareness, a proper management plan, and greater thrust on ecological research on mangrove ecosystems may help save and restore these unique ecosystems. It is significant for coastal ecosystem-based management with non-linear ecological functions and values given priority to restore and sustainably manage the depleting stocks of mangroves [68]. On the other hand, a trans-disciplinary approach to the long-term retrospection on mangrove development also can be used [69]. The loss and degradation of mangrove trees could lead to depleting stocks of coastal marine life [70]. Indeed, this is what has happened in many parts of the tropics, where developing countries (such as Malaysia) that need to develop land for a multitude of purposes resort to clearing the mangroves. At least 35% of the area of mangrove forests has been lost in the past two decades, losses that exceed those for tropical rainforests and coral reefs, two other well-known threatened environments [17]. For various reasons, ranging from the expansion of coastal towns, building airport runways and the construction of coastal roads, Peninsular Malaysia has lost around of a third of its mangroves (from an original area of around 150,000 ha to less than 100,000 ha today). Inshore fishermen throughout the world have noticed a remarkable decline in their catch following mangrove clearance.

Mangrove species are uniquely adapted to tropical and subtropical coasts, and although relatively low in number of species, mangrove forests provide at least US $1.6 bil each year in ecosystem services and support coastal livelihoods worldwide. Globally, mangrove areas are declining rapidly as they are cleared for coastal development and aquaculture and logged for timber and fuel production. Little is known about the effects of mangrove area loss on individual mangrove species and local or regional populations. To address this gap, species-specific information on global distribution, population status, life history traits, and major threats were compiled for each of the 70 known species of mangroves [71]. Each species' probability of extinction was assessed under the Categories and Criteria of the IUCN Red List of Threatened Species. Eleven of the 70 mangrove species (16%) are at an elevated threat of extinction. Particular areas of geographical concern include the Atlantic and Pacific coasts of Central America, where as many as 40% of mangrove species present are threatened with extinction. Across the globe, mangrove species found primarily in the high intertidal and upstream estuarine zones, which often have specific freshwater requirements and patchy distributions, are the most threatened because they are often the first cleared for development of aquaculture and agriculture. The loss of mangrove species will have devastating economic and environmental consequences for coastal communities, especially in those areas with low mangrove diversity and high mangrove area or species loss. Several species at high risk of extinction may disappear well before the next decade if existing protective measures are not enforced.

A comparison between sustained yield management for forestry and conversion to aquaculture shows that aquaculture development is economically precarious. A conservation plan involving sustained yield management and the establishment of mangrove national parks has been suggested. Seed materials from the national parks will ensure genetic vigor for sustained yield management. The economic and ecological effects of policies in Malaysia for the replacement of mangrove forests by aquaculture ponds have been studied [27]. Circumstantial, but not quantitative, evidence is presented of the dependence of the fishing industry on mangroves, with implications for employment. The sustained-yield production of timber in parts of Malaysia is noted. Plans to provide employment and food by large aquaculture schemes are criticized on purely financial grounds.

Ironically, one of the main causes of mangrove clearance is for farming seafood in aquaculture ponds. Since shrimp farms can produce much more shrimp than an equivalent area of mangrove, they may appear to be a good idea. However, there are many problems associated with aquaculture. Large-scale aquaculture in particular appears to be unsustainable – while high production and profits are possible in the short term, in the long term shrimp farms require more and more chemical inputs to achieve the same yield. Indeed, intensive shrimp farms seldom last more than 10 years before they have to be abandoned due to self-pollution and disease. Once a pond is abandoned, the owner often seeks new areas of mangrove to clear, diminishing the remaining forest reserves.

In addition to declining fish stocks, the loss of the mangroves is of direct concern to the numerous other creatures that live in the mangroves, including hundreds of species of birds (both migratory and resident), monkeys, and lizards (such as the huge monitor lizard). Furthermore, mangrove forests can be sustainably exploited for the production of wood for charcoal, firewood, and poles. Last year another incentive for mangrove protection became painfully clear when the December 26 tsunami flooded the coasts of the Indian Ocean [72]. While this disaster killed 68 people in Malaysia, this number is relatively low compared with neighbouring countries. Nevertheless, it led many to point

out that areas with intact mangroves were better protected against the destructive force of the waves. Mangroves should be protected along the length of all coastlines where they are found. In addition, a network of protected areas dotted along the coastline will provide 'stepping stones' for birds to move from along the coast. Generally speaking it is a good idea for a buffer of at least 400 m of mangroves to be kept along the coast and up estuaries where mangroves occur. However, this is not always possible as coastal development and reclamation would be bound to infringe into the buffer. In such instances it is important to ensure that pockets of mangrove forest be retained at strategic intervals along the coast. These areas will be our biodiversity treasure chests – havens for wildlife as well as seed-sources to enable the restoration of mangroves along the coast after the reclamation has been completed.

As an example, in Malaysia there have been successes and failures in the protection of mangroves. While our official guidelines provide for buffer strips and "permanent forest reserves," implementation does not always match the policy. Analysis of satellite imagery of the coasts of the states of Penang and Selangor shows how large areas of mangrove have been cleared for shrimp farms right up to the edge of the sea – without leaving an adequate buffer. This mangrove clearance often takes place despite the fact that the forest had previously been categorized as a "permanent reserved forest." Despite the terminology, in actual fact the state governments often give preference to development and revoke the status of forest reserves. In the last 10 years Penang, for example, has lost a fifth of its mangroves classified as permanent forest reserves. However, there are some positive signs with states such as Melaka creating new mangrove reserves such as the Ujong Pasir Bird Sanctuary in 2004 – even before the Prime Minister's call to protect the mangroves. Going north along the Melaka coastline, Ujong Pasir is supplemented by the Kuala Linggi Mangrove Forest Reserve. And further north still is the Tanjong Tuan Wildlife Reserve – recently extended to ensure greater protection to the wildlife of the area (as logging is not permitted in wildlife reserves). Policy makers in Malaysia appear to beginning to realize the importance of a network of intact coastal forests, not least for their potential to attract tourists keen on seeing the birds that congregate in such areas.

The loss of individual mangrove species and associated ecosystem services has direct economic consequences for human livelihoods, especially in regions with low mangrove species diversity and low ecosystem resilience to species loss. In the Gulf of California, for example, where there are only four mangrove species present (*Avicennia germinans*, *Rhizophora samoensis*, *Laguncularia racemosa*, *Conocarpus erectus*), it is estimated that one linear kilometer of the species *R. samoensis*, listed as Near Threatened, provides up to 1 ha of essential marine habitat and provides a median annual value of US$37,000 in the fish and blue crab fisheries [73]. Nutrients and carbon from mangrove forests provide essential support to other near-shore marine ecosystems such as coral reefs and seagrass areas, and enrich coastal food webs and fishery production [14, 20].

Avicennia species are dominant in inland or basin mangrove forests in many parts of the world. However, 3 of 8 (38%) species in this genus are in threatened or Near Threatened categories. Loss of these species and the mangrove forests they dominate will have far-reaching consequences for water quality and other near-shore ecosystems in coastal communities around the globe. For example, water purification services provided by these mangrove species in the Muthurajawela Marsh, Sri Lanka, are valued at more than US$ 1.8 mil/year [74].

Riverine or freshwater-preferring species, such as the Endangered *Heritiera fomes* and *Heritiera globosa*, buffer coastal rivers and freshwater communities from sedimentation, erosion, and excess nutrients. *Heritiera globosa* is a very rare species confined to western Borneo, while *Heritiera fomes* is more widespread in south Asia, but has experienced significant declines in many parts of its range. Localized or regional loss of these coastal or fringe mangrove species reduces protection for coastal areas from storms, erosion, tidal waves, and floods [68, 75], with the level of protection also dependent on the quality of remaining habitat [69]. Two of four (50%) fringe mangrove species present in Southeastern Asia (*Sonneratia griffithii*, *Aegiceras floridum*) are listed in threatened or Near Threatened categories. In other areas, such as Brazil, the central Pacific islands, or West Africa, fringe mangrove forests are often comprised of only one or two species. Even though these species are globally listed as Least Concern, local and regional loss of mangroves in these areas will have devastating impacts for coastal communities. The loss of species may indeed be of greatest economic concern in rural high-poverty areas where subsistence communities rely on mangrove areas for fishing and for direct harvesting of mangroves for fuel, construction, or other economic products [76-78]. Finally, it is important to note that the amount of mangrove area in some countries is increasing due to reforestation and restoration efforts [5]. Although regeneration of degraded mangrove areas is thought to be a viable option in some areas [76], successful regeneration is generally only achieved by the planting of monocultures of fast-growing species, such as *Rhizophora* or *Avicennia* species. Many rare and slow-growing species are not replaced [5], and many species cannot be easily replanted with success. In sum, mangrove areas may be able to be rehabilitated in some regions, but species and ecosystems cannot be effectively restored.

Geospatial Information Tools for Monitoring, Mapping and Inventories of Mangrove Forest

Remote sensing, either airborne hyperspectral [79] or satellite-based [80-84], captures spectral and spatial characteristics of mangrove areas and therefore can be an efficient method to estimate vegetation cover, as well as density and structure [85-88]. The benefits of these methods are that they can produce spatially explicit information at various scales, ranging from less than 1m (aerial photography) to 180 km; they are able to collect information in inaccessible areas and may allow for repeated coverage.

There are a number of different sensor types, each with its own benefit and limitation, as well as a suite of different data classification and interpretation methods. It is worth noting that remote sensing data deals with the most typical, well-tested methods, and that the pace of technology development in this field is fast. Therefore, this paper may not fully capture some of the newer operational methods for automated mapping of mangrove biomass cover. However, it has been proven that L-band ALOS PALSAR data had successfully predicted aboveground biomass for tropical forests [89]. In fact, the IUCN Red List assessments for mangrove species can be regularly updated, depending on the availability of better or new data, and any subsequent changes in a species Red List Category can be an important indicator of the success or failure of conservation actions. As the impacts of mangrove area loss on mangrove species can be variable, estimation of species composition, individual species decline, or population size in a given area can be better refined by available remote sensing techniques [63, 90-94]. Similarly, demographic modelling is needed to establish a minimum viable population size for mangrove species, especially for those that are highly threatened [95]. As ecosystem values can be overestimated or underestimated, additional studies and cost/benefit analyses are needed to determine the economic and ecological impacts of harvesting, habitat loss, and habitat deterioration on populations of individual mangrove species.

The strong correlation between aboveground biomass and radar backscattering coefficient in HV polarization from ALOS PALSAR image had produced an alternative for assessing aboveground biomass, which was one of the most important forest stand parameters. Overall, the aboveground biomass values ranged from 25.9 ± 10.9 to 569.3 ± 10.9 t·ha^{-1} that covered all types of standing forests. From this information, a spatially distributed map that showed spatial pattern of aboveground biomass for the whole study area was produced. Aboveground carbon stocks were between 12.95 ± 5.45 and 284.65 ± 5.45 t C·ha^{-1}. Natural and mature standing of planted forests showed higher concentration of living biomass compared to some regions with less or sparsely distributed mature, big, and tall trees. Results also indicated that despite its limitations, the use of L-band SAR could provide an alternative for rapid assessment of biomass as well as carbon stocks in a large area. There are several important criteria for selecting remote sensing data and products for terrestrial carbon inventory [96], including:

(i) Adequate land-use system stratification scheme. Stratification of the project area has to be robust and clear enough to be able to distinguish between them. The stratification should be of adequate spatial resolution to enable the use of remote sensing.

(ii) Appropriate spatial resolution. If broad categories or distinct land-use differences are sought, such as forested and non-forested land, low-resolution remote sensing might be adequate. In comparison, a detailed categorization of different agricultural lands requires high resolution.

(iii) Appropriate temporal resolution. Estimating land use changes in boreal forest systems might require data that span over decades. On the other hand, for estimating changes in grassland, data for even a single year may be sufficient. Seasonality of the vegetation is an important factor since peak vegetation period is usually the best time for inventory of terrestrial carbon.

(iv) Availability of historical assessment. Often the limitation of conducting a remote sensing survey is the availability of historical data. In that sense the future is promising, since more, readily available sensors and products are being developed.

(v) Transparent and consistent methods are applied in data acquisition and processing. Since carbon inventories are performed frequently and require monitoring over time, the methods used have to be repeatable.

(vi) Consistency in data and availability over time. The products used should be consistent over time for the same reason as stated in point five, above. The paper presents a method based on the time series of satellite image, which can save time and money, greatly speed up the process of urban forest carbon storage mapping, and possibly, regional forest mapping [97].

It has been confirmed that mangroves are among the carbon-rich forests in the tropics [98]. Satellite imagery collected in different years can be used to develop a regression equation to predict the urban forest carbon storage from normalized difference vegetation index (NDVI) computed from a time sequence of LANDSAT image data [97]. The results demonstrate the rapid and cost-effective capability of remote sensing-based quantitative change detection in monitoring the carbon storage change and the impact of urban forest management over decades. The studies imply that image analyses can produce estimates of carbon storage from urban trees reasonably well and image normalization procedures offer a promising method for detecting changes over time. Although this study simplified some complex analysis through image processing, it also showed that the potential payoff could be substantial. Fig. 4 shows the estimated biomass maps calculated by the NDVI and Radarsat fine mode [99]. The study was carried out in Guangdong Province in South China. A comparison was made between the images of Landsat™ and those of Radarsat; regression and analytical models were used to establish the relationship between remote sensing and mangrove biomass. Results showed that Radarsat fine mode images have significant accuracy improvement in terms of root mean square error (RMSE), whereas the use of the single NDVI may produce much error in biomass estimation. The Radarsat images can obtain more accurate trunk information about mangrove forests because of higher resolution and side-looking geometry. The study can be repeated and extended geographically to gain more economical and timely estimation of the biomass resource and improve environmental management continuously.

A Fourier-based textual ordination (i.e. principal components analysis of Fourier spectra) with IKONOS near-infrared and panchromatic imagery was used to estimate biomass, based on detection of canopy structure as shown

Fig. 4. Biomass estimated from the NDVI (left) and backscatter models (right).

in Fig. 5 [100]. Results showed that there was a significant non-linear relationship between the tree stage (e.g., pioneer, mature, dead) and the principal components of the Fourier spectra. The best model used the panchromatic imagery with a 30 m window and explained over 90% of the total and trunk biomass with a relative error of 16.9%. The P-band PolSAR most accurately estimates tree height and aboveground biomass, although the HV polarization of L-band SAR also performs well, explaining 93%, 96%, and 94% of basal area, tree height, and aboveground biomass, respectively [101]. The relationships between PolSAR coefficients and biomass, however, are non-linear and change signs with multiple times over the biomass range. In a follow-up study, PolSAR signal modelling illustrated difficulties in predicting the interaction of PolSAR with three-dimensional heterogeneous components, specifically interactions between soil surface, trunk, and canopy volume

components [102], and was later confirmed [103]. In pioneer and declining mangrove stands, a substantial fraction of scattering was due to the interaction of surface and canopy volume components. It was concluded, based on model results that statistical relationships of PolSAR to biomass were limited to homogeneous closed canopies where interaction effects were less pronounced. In a separate study, using AIRSAR to assess the potential of space-borne L-band PolSAR, it was noted that L-band HV data could delineate different mangrove zones based on species and biomass/stage, but that the separation of surface, volume, and interaction components from the PolSAR signal remained a significant challenge due to inconsistent empirical results [104]. The implications of these results suggest that a given SAR signal results from different combinations of forest structure.

The Significant Values, Economic Uses, and Productivity of the Mangroves

Information on the array of mangrove products and services used, understood, and perceived at the local level may help decision makers, stakeholders, and others make better resource management decisions. Qualitative research methods can reveal information on ecosystem products and services at the local level. In-depth interviews have been used to collect data on local use of mangrove wood and wood products. The beneficiaries about the array of ecosystem products and services associated with a mangrove ecosystem showed that the local resource beneficiaries do not view wood products as the most important service of the mangrove ecosystem [105]. However, it was reported that the different kinds of goods and services that mangrove forests provide to society and communities are widely understood but may be too generally stated to serve as useful guidelines in decision-making [36, 75]. Understanding the differences between fringe, riverine, and basin forests may help to focus these guidelines and to determine the best use of a particular forest. Fringe mangroves are important primarily for shoreline protection. Riverine forests, which
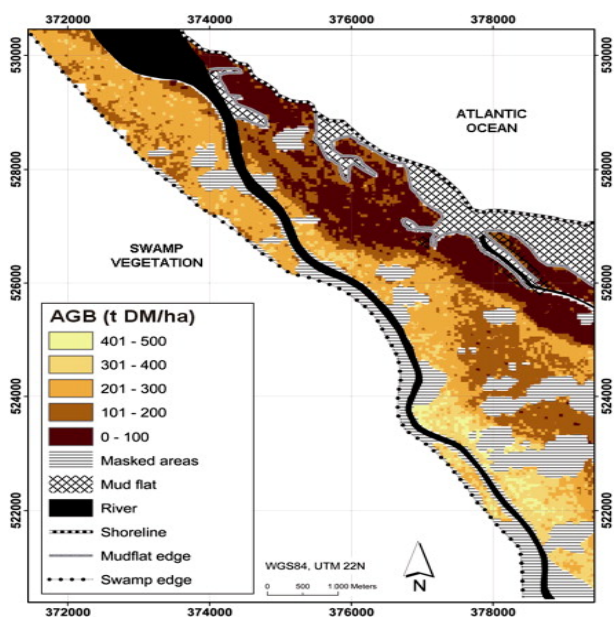

Fig. 5. Derived aboveground biomass estimates of the Kaw site in French Guiana, South America.

are likely to be the most productive of the three types of forests, are particularly important to animal and plant productivity, perhaps because of high nutrient concentrations associated with sediment trapping. Basin forests serve as nutrient sinks for both natural and anthropogenically enhanced ecosystem processes and are often important sources of wood products. Exploitation of a forest for one particular reason may make it incapable of providing other goods and services. The importance of mangroves to the global community has long been stressed [7]. For example, the mangrove inlets and creeks in Selangor, Malaysia are the habitat for 119 species of fish and nine species of prawns. The majority of fish and all prawns sampled in the inlets were juveniles [106]. The common fish species in the inlets in terms of weight were *Arius sagor*, *Ambassis gymnocephalus*, *Liza subviridis*, *Toxotes jaculator*, *Sphyraena barracuda,* and *Lates calcarifer*. Prawns were represented by juvenile *Penaeus penicillatus*, *P. merguiensis*, *P. indicus*, *Metapenaeus brevicornis,* and *M. affinis.* Samples from enclosure traps set on mudflats during ebbing water captured 37 species of fish and 11 species of prawns. The role of mangroves as nursery and feeding grounds for fish and prawns is reviewed in the light of recent work in Selangor. It is apparent that mangroves support fisheries by providing habitat and food.

The economical uses of products from mangrove ecosystems are many and varied. Traditionally, the mangroves have been exploited for firewood and charcoal. Use also has been found for mangroves in the construction of dwellings, furniture, boats and fishing gear, and tannins for dyeing and leather production. The mangroves provide food and wide variety of traditional products and artefacts for the mangrove dwellers. Mangroves' falling leaves, flowers, and fruits supply more than 3 kg/m²/yr of organic matter to be decomposed by bacteria and fungi and returned to the food chain. The biodiversity of the dense mangrove root systems multiplies the available space for other organisms, offering them a large number of microhabitats in a confined space. Countless fish, crustaceans, and bivalves populate the water. The roots of the trees are colonized by algae, barnacles, oysters, sponges, and molluscs. In the free-flowing channels, pistol shrimps and fish abound. Large numbers of fiddler crabs are found on the silt surfaces. The upper storeys of the mangrove forest overhead are home to reptiles, birds, and mammals. Sea cows head for the sheltered mangroves to calve, and monkeys catch crabs on the shore. Extracts and chemicals from mangroves are used mainly in folkloric medicine (e.g. bush medicine), as insecticides and pesticides, and these practices continue to this day. However, the extraction of novel natural chemical compounds from mangroves, in addition to those already known to the pharmacopoeia of the people, is in its infancy. Knowledge of the biological activities and/or chemical constituents of plants is desirable, not only for the discovery of new therapeutic agents, but because such information may be of value in disclosing new sources of already known biologically active compounds. It is of further value to those interested in deciphering the actual value of folkloric remedies.

The growth of selected *Rhizophora apiculata* (*Rhizophoraceae*) trees has long been monitored (from 1920 through 1981) in a 0.16 ha plot of protected forest in the Matang Mangroves [23]. Starting in 1950, the sample was increased to include monitoring the growth of all the trees more than 10 cm dbh (diameter at 1.3 m or above prop roots). All seedlings were censured by species and removed in 1920 and re-censured in 1926, 1927, and 1981. Total above-ground dry weight (biomass) of the forest was estimated using stand tables and a regression equation of biomass on dbh calculated for destructively sampled *R. apiculata* trees from elsewhere in the Matang Mangroves. Net primary productivity (1950-81) was calculated from estimated biomass increments and published litter-fall rates. *Rhizophora apiculata* has maintained its dominance of the plot since 1920, but *Bruguiera gymnorrhiza* (*Rhizophoraceae*) and several other more shade-tolerant species have steadily increased in abundance. Between the 1920's and 1981, *R. apiculata* declined in relative abundance in the seedling layer while *B. parviflora* and *B. cylindrica* increased. Mean mortality rate (1950-81) for trees more than 10 cm dbh was 3.0% per year with a range of 1.3-5.4% per year. When trees fell over and hit other trees, the damaged trees usually died within 10 years. A major cause of mortality appeared to be sapwood-eating termites. Net primary productivity averaged 17.7 t/ha/year over the 1950-81 observation period. Biomass ranged from 270 to 460 t/ha with a mean of 409 t/ha. It is suggested that *Rhizophora* spp. trees greater than 50 cm dbh and mangrove forests with total above-ground biomass exceeding 300 t/ha would develop in other areas outside of the region affected by hurricanes if the forest was protected from human disturbance.

The mangrove ecosystem in many wet tropical areas represents one of the most (if not the most) productive of natural ecosystems. The question that has occupied the minds of many mangrove scientists is "What is the fate of this high productivity"? More recently this question has gained added relevance as a result of the increase in global carbon dioxide concentrations. Are mangroves sinks of atmospheric carbon? We try to answer these questions using 15 years of data from the Matang Mangrove Forest Reserve and the Sungai Merbok Forest Reserve in Peninsular Malaysia. We take a quick look at the palaeo-geological evidence on sea level changes in the Straits of Malacca during the recent past (Holocene) to give us a better perspective of the Matang and Merbok mangroves and emphasize the dynamics and ephemeral characteristics of the mangrove ecosystem. The pristine forest of Matang has a mean net annual above-ground productivity of 18 t dry organic matter/ha/yr, whereas the same forest managed on a sustained yield basis is a good 20% more productive. If harvested timber is used as fuel wood, then much of what is fixed is released back into the atmosphere. On the other hand, if harvested timber is used as pilings, then significant amounts of mangrove carbon are locked away. It was estimated that for the mangroves of Matang some 1.5 tC/ha/yr is buried each year over the past 8,000 years or so [107]. The impact of man (since the beginning of this century) has

resulted in an initial increased release of carbon into the atmosphere (in the first half of this century) as a result of the use of mangrove timber as fuel-wood, but sustained yield management has ensured a carbon balance between what is fixed as timber and what is burned. The present management system (which produces significant amounts of slash and stumps) may result in increased amounts of burial (i.e. more than the 1.5 tC/ha/yr). To demonstrate that the terms "source" and "sink" are relative terms, we show that mangroves may (at the same time as being a sink for atmospheric carbon) also be a source of carbon in that they may out-well significant amounts of carbon to adjacent coastal ecosystems and thus play a vital role in coastal fisheries production. Conversion of mangrove to aquaculture ponds could result in the release (from about 1,000 years accumulated mangrove sediments) of some 75 tC/ha/yr to the atmosphere over a 10-year period. This is 50 times the sequestering rate.

Wood

Historically, many mangrove forests have provided useful products such as timber, fuel, railroad ties, tannin, poles, firewood, and charcoal. Having a short crop rotation period makes red mangroves a popular choice for posts and poles in the well managed mangrove forests of Malaysia. Mangrove forests are also a valued source of wood products for many coastal communities [37, 108-112]. Most mangrove tree species produce wood that is extremely hard and also burns hot. Mangrove wood is often preferred for use as a cooking fuel and for construction of fish traps, wharves, fences and roofing. In some parts of Asia, commercial mangrove production is necessary for the construction of boats, houses and furniture. Malaysian mangrove forests, however, are no longer harvested commercially for timber. In the Philippines, field measurements confirm ethnographic evidence indicating that harvesting for construction wood, but not fuel wood, is both species and size-selective [29].

The wood of the tree has a high calorific value, meaning it produces high heat when burned, making it the wood of choice in the manufacture of charcoal in Malaysia, Indonesia and Thailand. Mangrove charcoal, either the branch or trunk types, is one of the heaviest charcoals used for BBQ in restaurants, outdoor picnic charcoal packs, and in some industrial applications like metal production. One advantage of this charcoal is it gives a special aroma to BBQ when burning.

Environment

Mangrove forests are naturally dynamic environments, subject to periodic fluctuations in climate and ever responsive to changes in sea level. Because of the longevity of individual mangrove trees they can provide a record of the effects of past changes in environmental conditions and of human influence in their structure and composition. Mangrove communities interact closely with other tidal vegetation such as salt marsh. There is evidence that these two ecosystem types cycle from one to the other depending on the amount of freshwater flushing that occurs, which in turn depends on changes in rainfall over nearby land. The future of mangrove forests in Malaysia is uncertain. While they demonstrate extraordinary adaptations to the estuarine environment, it is expected that changes such as sea level rise and increased storm severity as a result of climate change will challenge their existence in some areas. They also face increasing pressure from coastal urbanization.

Mangroves play important roles in the ecology of wetlands and estuaries. In addition to branches of corals, mangroves can be counted as an important carbon sink of tropical oceans. They are able to regulate the global natural balance and have similar effects to peat land carbon sinks; through sedimentation they can accumulate perpetually organic matter and harmful substances and abstract them from the cycle of matter. Approximately 200 m of mangroves are able to scale down the power of a marine surge to 75%. As a result of adherence of oceanic sediments, intact mangroves can cope with the temporary swelling of sea level that accompanies it [113]. In the case of a potential sea level rise as a consequence of human development, the mangroves would lose the ability to protect their habitats. An important regulatory factor for the stabilization of global nature processes would fail.

By reducing the speed of currents and trapping sediments, mangroves protect the shoreline from erosion and help to reduce silt accumulation in adjacent marine habitats. In addition, river-borne nutrients and chemicals are trapped and recycled within these communities. Mangroves are highly valued for their unique biodiversity. They provide habitat and breeding sites for a wide variety of birds, fish, amphibians, insects, small mammals, and other aquatic fauna. Several rare species are found in mangrove ecosystems, such as the rusty monitor, which utilizes the hollows of mature or dead mangrove trees.

Reduce Impact of Tsunamis

Dense mangrove forests growing along the coasts of tropical and sub-tropical countries can help reduce the devastating impact of tsunamis and coastal storms by absorbing some of the waves' energy, say scientists. For example, when a tsunami struck India's southern state of Tamil Nadu on 26 December 2004, areas in Pichavaram and Muthupet with dense mangroves suffered fewer human casualties and less damage to property compared to areas without mangroves [67]. Mangroves often serve as a barrier to the fury of water, and they reduced the impact of a 'super-cyclone' that struck Orissa in 1999 on India's east coast, killing at least 10,000 people and making 7.5 mil. homeless [114]. Mangrove forests have been observed to play a role in reducing tsunami wave heights if the heights are not too high, or are less than 3 m. Measurement of wave forces and modeling of fluid dynamics suggest that tree vegetation may shield coastlines from tsunami damage by reducing wave amplitude and energy. More details on TUNA modeling of Andaman tsunami impact in Malaysia (coasts of Penang and Kedah) and Indonesia (Acheh) by mangroves have been well documented [115, 116].

Mangrove systems minimize the action of waves and thus prevent the coast from erosion. The reduction of waves increases with the density of vegetation and the depth of water. This has been demonstrated in Vietnam [117, 118]. In the tall mangrove forests, the rate of wave reduction per 100 m is as large as 20%. Another work has proved that mangroves form 'live seawalls', and are very cost effective as compared to the concrete seawall and other structures for the protection of coastal erosion [119]. Analytical models show that 30 trees per 100 m^2 in a 100-m wide belt may reduce maximum tsunami flow pressure by more than 90% if the wave height is less than 4-5 m [120]. It was also reported that six-year old mangrove forests of 1.5 km width reduce waves by 20 times, from 1 m high in the open sea to 0.05 m at the coast [117]. The reduction of wave amplitude and energy by tree vegetation also has been proven by measurements of wave forces and modeling of fluid dynamics [121].

Cuddalore District in Tamil Nadu, India, provides a unique experimental setting to test the benefits of coastal tree vegetation in reducing coastal destruction by tsunamis [122]. At the river mouth, the tsunami completely destroyed parts of a village and removed a sand spit that formerly blocked the river. However, areas with mangroves and tree shelterbelts were significantly less damaged than other areas (supporting online text). Damage to villages also varied markedly. The villages on the coast were completely destroyed, whereas those behind the mangrove suffered no destruction even though the waves damaged areas unshielded by vegetation north and south of these villages. Mangroves attenuated tsunami-induced waves and protected shorelines against damage. Conserving or replanting coastal mangroves and greenbelts should buffer communities from future tsunami events. All these works revealed that mangroves are more effective than concrete seawall structures for reducing tsunami-hit house damage behind the forest.

Indigenous and Medicinal Values

Numerous mangrove plants are used in folklore medicine. Extracts from mangroves and mangrove-dependent species have proven effective against human, animal, and plant pathogens, but only limited investigations have been carried out to identify the metabolites responsible for their bioactivities. Skin disorders and sores – including leprosy – may be treated with ash or bark infusions of certain species of mangrove. Reported to be an astringent, emmenagogue, expectorant, hemostat, styptic and tonic, red mangrove is a folk remedy for angina, asthma, backache, boils, constipation, convulsions, diarrhoea, dysentery, dyspepsia, elephantiasis, eye ailments, fever, fungal infections, headaches, haemorrhage, inflammation, jaundice, kidney stones, lesions, malaria, malignancies, rheumatism, snakebites, sores, sore throat, syphilis, toothache, tuberculosis, ulcers, and wounds. A cure for throat cancer by gargling with extract of mangrove bark has been reported in Columbia. The traditional and medicinal uses of mangroves have been reviewed and recent investigations on the biological activi-

ties of extracts and chemicals identified from mangroves (mangroves, mangrove minors, and mangal associates) [123]. It describes how people have and are using mangroves on a traditional basis. It also describes the world's mangrove resources and products, in terms of their economic importance, medicinal values, and other uses and functions.

The bark, leaf shoots and roots of the trees supply tannin used for dyes, leather preservatives, and furniture stains. The mangrove sap can be used to make the black dye for tapa cloth while the leaves are used for livestock food, as "green manure" in fishponds, and as tea and tobacco. Mangroves are being studied as a source of pesticides and agrochemical compounds. Toxins found in mangroves may play a future roll in repelling insects. Resin extracted from the tree is used in producing plywood adhesives. The manufacture of chipboard and pulpwood (newspaper and cardboard), all depend on by-products of the red mangrove. The ash of the red mangrove is used as a soap substitute and other mangrove extracts are used to produce synthetic fibers such as rayon, and cosmetics. Mangrove worms, found within decaying mangrove wood, are collected for food. The fruits are said to be edible and flowers are a source of honey and fish poison. The timber is used for implements, firewood, and construction. Some Malaysian fishermen harvest many edible fish and shellfish from mangrove ecosystems.

Other Uses

One of the key beneficiaries of mangroves is the fishing and tourism industry. Mangrove forests constitute breeding nurseries for a high proportion of Malaysia's commercial and recreational fish catch, including barramundi (*Lates calcarifer*), and banana prawn (*Penaeus merguinensis*). An estimated 75% of the fish and prawns caught for commercial and recreational purposes in Malaysia spend at least part of their life cycles in mangroves. Mangroves also provide protection for both the natural and built environments from waves and storm surges. Some species have leaves that are palatable for livestock when other food is unavailable. Mangrove forests provide a focus for tourism in some coastal communities. Boardwalks in particular are popular with tourists and provide an opportunity for educating people about the ecological and economic importance of mangroves.

Distributions of dissolved nutrients and Chl. *a* was investigated in the Sangga Besar River Estuary in the well-managed Matang Mangrove Forest in Malaysia [124]. In the estuary, spring tide concentrations of ammonium, silicate, and phosphate were higher than those in the neap tide, which suggests that these nutrients are flushed from the mangrove area by the inundation and tidal mixing of the spring tide. Ammonium comprised over 50% of the dissolved inorganic nitrogen in the spring tide, while nitrite tended to dominate in the neap tide, indicating the predominance of nitrification inside the estuary in neap tides. Nutrient concentrations in the creek water were higher than those of estuarine water, indicating the nutrient out-

welling from the mangrove swamp and ammonium regeneration from mangrove litter in the creek sediments. The maximum concentration of Chl. *a* in spring tides reached 80 ug/l, while it was below 20 ug/l in the neap tides. These variations in the phytoplankton biomass and nutrients probably reflect the greater nutrient availability in the spring tide due to outwelling from the mangrove swamp and creek.

The ecological benefits of the mangrove forests are considered to be proven, in terms of soil stabilization and prevention of erosion, while those of the aquaculture schemes are thought to be, at least, uncertain, particularly in view of the 'haphazard' nature of the schemes. It is recommended that conversion schemes should only proceed with extreme caution and should be carefully evaluated both ecologically and socioeconomically. Mangrove forests provide an important ecosystem service of safeguarding human societies from natural disasters along tropical coastal zones. With recent major coastal disasters, including the South Asian tsunami in 2004 and the observed protection buffer that mangroves have provided, evaluating mangrove ecosystems for protecting coastal areas from natural disasters is a necessity for appropriate conservation planning of ecosystem services. The avoidance and replacement costs of mangrove ecosystems in South Asia, in reference to the South Asian tsunami of 2004, was assessed [12]. The findings demonstrate that the coastal protection value of mangroves exceeds direct-use values of mangroves, such as forest harvesting and mariculture by over 97%. Mangrove ecosystems are highly valuable for protection against natural coastal disasters, and their conservation and restoration are needed to maintain national and global natural capital.

Mangroves are ecologically important coastal wetland systems that are under severe threat globally. In Thailand, the main cause of mangrove conversion is shrimp farming, which is a major source of export income for the country. However, local communities benefit from many direct and indirect uses of mangrove ecosystems and may have a strong incentive to protect these areas, which puts them into direct confrontation with shrimp farm operators and, by proxy, government authorities. This article examines whether or not the full conversion of mangroves into commercial shrimp farms is worthwhile once the key environmental impacts are taken into account. The estimated economic value of mangrove forests to a local community is in the range of US$27,264-US$35,921/ha [126]. This estimate includes the value to local communities of direct use of wood and other resources collected from the mangroves, as well as additional external benefits in terms of off-shore fishery linkages and coastline protection from shrimp farms. The results indicate that, although shrimp farming creates enormous private benefits, it is not so economically viable once the externalities generated by mangrove destruction and water pollution are included. There also is an incentive for local communities to protect mangroves, which in turn implies that the rights of local people to guard and protect this resource should be formally recognized and enforced by law.

The term nursery implies a special place for juvenile nekton (fishes and decapod crustaceans) where density, survival, and growth of juveniles and movement to adult habitat are enhanced over those in adjoining juvenile habitat types. Most studies of mangroves as nurseries have addressed only the occurrence or density of fish or decapods, have not used quantitative sampling methods, and have not compared alternate habitats. Comparison of nekton densities among alternate habitats suggests that, at times, lower densities may be typical of mangroves when compared to seagrass, coral reef, marsh, and non-vegetated habitats. There is little direct consumption of mangrove detritus by nekton. C, N, and S isotope studies reveal little retention of mangrove production by higher consumers. The densities of prey for transient fish and decapods may be greater within mangroves than elsewhere, but there has been no verification that food availability affects growth or survival [127]. Experimental evidence indicates that mangrove roots and debris provide refuge for small nekton from predators, thus enhancing overall survival. There is no evidence that more individuals move to adult habitats from mangroves than from alternate inshore habitats. There is an obvious need to devise appropriate experiments to test the nursery functions of mangroves. Such data may then be one more reason to add support for mangrove conservation and preservation.

Vegetated coastal ecosystems provide goods and services to billions of people. In the aftermath of a series of recent natural disasters, including the Indian Ocean Tsunami, Hurricane Katrina, and Cyclone Nargis, coastal vegetation has been widely promoted for the purpose of reducing the impact of large storm surges and tsunamis. The use of coastal vegetation as a "bioshield" against these extreme events was reviewed with an objective to alter bioshield policy and reduce the long-term negative consequences for biodiversity and human capital [128]. The science of wave attenuation by vegetation and case studies from the Indian subcontinent and evaluating the detrimental impacts that bioshield plantations can have upon native ecosystems (drawing a distinction between coastal restoration and the introduction of exotic species in inappropriate locations) were discussed. Bioshield policies were placed into a political context, and outline a new direction for coastal vegetation policy and research [128].

Research Progresses on Mangroves in Malaysia

Mangrove research in Malaysia began in the early 1950s and has been well developed during last five decades. Early work focused mainly on mangrove floristic, taxonomy, population ecology, and community and vegetation distributions. Since then, a significant amount of books and scientific papers have been published, indicating the rapid development in this research field. Although the number of research papers published by Malaysian scientists doubled after 2000, world mangrove research developed more rapidly based on the total number of published science citation index (SCI) papers. Between 1990 and 2007

mangrove research in Malaysia focused on a dozen areas that included remote sensing and modeling, aquaculture, global ecology, geography and hydrography, energy flow, morphology and anatomy, molecular ecology, pharmaceuticals and active material exploitation, silviculture, community and population ecology, biodiversity, pollution ecology, ecophysiology, conservation, and management. Among them, five research areas increased most rapidly, including molecular ecology, pollution ecology, biodiversity, conservation and management, silviculture and pharmaceuticals, and active material exploitation.

Extensive research on mangrove ecosystem structure and function has revealed extremely high biomass and primary production for the mangrove forests in Malaysia. The highest biomass among Malaysian mangrove forests was found in the Matang mangrove forest in Perak, with the biomass of 248.5 t/ha, followed by the *R. stylosa* forest in Shankou Nature Reserve in Guangxi (196.2 t/ha), and the *K. obovata* forest in Hong Kong (129.6 t/ha) [129, 130]. High litter production and litter decomposition rates also were found in the Malaysian mangrove communities [129, 131, 132]. Based on these results, a "Three-High" or "3-H" theory on mangrove communities, i.e. high productivity, high return ratio and high decomposition ratio, was later proposed [133]. There were increasing interests in studies on the interactions between Malaysian mangrove ecosystems and global change. However, so far the work has focused mainly on methane dynamics in mangrove wetlands [134, 135] and the responses of mangroves to tidal flooding associated with sea level rise [136, 137]. Little is known about how mangroves and their ecosystems in Malaysia respond to elevated CO_2, global warming or nitrogen deposition. Thus, more studies in this field are urgently needed to assess potential impact of global change on the mangroves in Malaysia.

A great deal of field and greenhouse studies have pointed to great challenges in selecting plantable tidal flats for the mangrove afforestation efforts in Malaysia. Mangrove can only occupy the tidal flats between the mean sea level (of slightly above) and the highest tidal level in the tropical region. Studies on mangrove management and new techniques in silviculture developed rapidly after 2000. Research on the potentials of mangrove wetlands for wastewater treatment and pollutant degradation also have been greatly promoted in Malaysia since the 1990s. Mangrove wetland was regarded as an effective ecological system for the removal of nutrients and other anthropogenic pollutants [62, 138]. Furthermore, the bacterial consortium enriched in mangrove sediments also was shown to be very effective in facilitating the degradation of many polycyclic aromatic hydrocarbons.

Medicinal applications of Malaysian mangrove plants were known for a long period of time, which stimulated great interests in the studies on the sources, compound structures, and bioactivities of natural products from mangrove materials after 2000. However, the direct utilization of mangrove materials for medicine production likely will reduce mangrove resources and should be avoided. A better way for this application is to formulate new medicines through chemical synthesis based on the compound configurations of related compounds found in certain mangrove materials. While in the field of molecular ecology, great progress has been made since 2000, especially in the areas of the geographical distances and species relationships of Malaysian mangroves. These studies illustrated the values of using modern geospatial information technologies in precision forestry with airborne hyperspectral imaging, global positioning system (GPS), and geographic information system (GIS) in resolving long-standing ecological or evolutionary issues in mangroves.

In short, future research on mangroves in Malaysia must involve more local communities with a focus on pioneering and innovative ways on how we can combine scientific knowledge with traditional ecological tacit knowledge to protect and sustainably manage our Malaysian mangroves. This includes evaluating mangrove ecosystems to support sustainable management, mangrove ecotourism-potential and constraints, post tsunami and other disaster preparedness issues, transboundary protected areas involving mangrove ecosystems, ecological engineering management approaches, and, last but not least, communications and knowledge management.

Future Perspectives of Mangrove Forests in Malaysia

Over the past two decades, a large number of case studies have significantly increased our understanding of the structure and function of the mangrove ecosystems as well as the value of mangroves. However, there are still many areas that need to be strengthened in the future. Firstly, the mangrove ecosystem functions in Malaysia have been studied intensively, but the question of which mangrove species is the keystone species of Malaysian mangrove ecosystems still has not been resolved. More controlled experiments on the relationships between species diversity and ecosystem functions of mangroves should be conducted to resolve this issue. Secondly, many studies have shown that mangroves would migrate landward and expand laterally into areas of higher elevations in response to sea level rise [139]. As pointed out earlier, the construction of sea walls, plus many skyscrapers behind natural mangrove wetlands, may prevent such migration from occurring, so there is a need to evaluate the fate of mangroves in Malaysia under rising sea levels in the coming decades. Thirdly, biological invasions of weed species may jeopardize mangrove habitats.

There still is a lack of good understandings of their invasive mechanisms and the efficient measures for controlling such invasions. More field and greenhouse studies are needed in this field. Fourthly, great efforts and achievements have been made in mangrove afforestation restoration in Malaysia, but there is still a lack of a universal standard system for evaluating such efforts and achievements. Collaborations among governmental agencies (such as the State Forestry Department), research institutions (FRIM), local universities (UPM, USM, UM, UKM, UMS, UNIMAS), and local communities are strongly encouraged for establishing such evaluation standard systems for man-

grove afforestation and restoration. Finally, cooperation among related mangrove research institutions in ASEAN is essential to ensure more successful conservation, restoration, and research of mangroves in the region. There has been continuous cooperation on mangrove research between Malaysia, Indonesia, Thailand, and Brunei since the 1990s, but more research collaboration in terms of governance, law, and policy between Malaysia and other ASEAN member countries is urgently required. It has to be recognized that restoring and protecting mangrove wetlands in all critical areas of Malaysia requires collaborative efforts from all parties.

Conclusion

With some exceptions, mangrove areas and species of concern are generally not adequately represented within protected areas in Malaysia. In addition to legislative actions, initiatives are needed on the part of governments, NGOs, and private individuals to acquire, rehabilitate, and protect parcels of coastal land, especially those that contain viable populations of threatened mangrove species. National legislation and management plans are in place in Malaysia, but enforcement and further planning are required to protect individual species that may be locally uncommon or threatened, as well as to protect the entire mangrove areas and important ecosystem functions. Probably, the Malaysian mangrove species are at risk of extinction and may disappear within the next decade if protective measures are not enforced. Their conservation should not be overlooked, especially as they are important for speciation and can be significant drivers of diversification over time. The loss of individual species will not only contribute to the rapid loss of biodiversity and ecosystem function, but will also negatively impact human livelihoods and ecosystem function, especially in areas with low species diversity and/or high area loss.

References

1. MARSHALL N. Mangrove conservation in relation to overall environmental considerations. Hydrobiologia: management issues, ecological, economics and other topics, **285**, (1-3), 303, **1994**.

2. GIESEN W., WULFFRAAT S., ZIEREN M., SCHOLTEN L. Mangrove guidebook for Southeast Asia. Food and Agricultural Organisation & Wetlands International, Bangkok, Thailand, pp. 769, **2007**.

3. DUKE N.C., MEYNECKE J.O., DITTMANN S., ELLISON A. M., ANGER K. U., BERGER S., DIELE C.K., EWEL K. C., FIELD C. D., N. KOEDAM S. Y. LEE MARCHAND C., NORDHAUS I., GUEBAS F. D. A world without mangroves? Science Letters. **6**, 41, **2007**.

4. ELLISON A.M., BANK M.S., CLINTON B.D., COLBURN E. A., ELLIOTT K., FORD C. R., FOSTER D. R., KLOEPPEL B. D., KNOEPP J. D., LOVETT G. M., MOHAN J., ORWIG D. A., RODENHOUSE N. L., SOBCZAK W. V., STINSON K. A., STONE J. K., SWAN C. M., THOMPSON J., VON HOLLE B., WEBSTER J. R.

Loss of foundation species: consequences for the structure and dynamics of forested ecosystems. Front Ecological Environment, **3**, 479, **2005**.

5. ALONGI D.M. Present state and future of the world's mangrove forests. Environ Conserv., **29**, 331, **2002**.

6. FAO. The World's Mangroves 1980-2005, FAO Forestry Paper 153. Rome: Forest Resources Division, FAO, pp. 77, **2007**.

7. DUKE N.C., PINZON Z.S., PRADA M.C.T. Large-scale damage to mangrove forests following two large oil spills in Panama. Biotropica, **29**, 2, **1997**.

8. DUKE N.C., BALL M.C., ELLISON J.C. Factors influencing biodiversity and distributional gradients in mangroves. Global Ecol. Biogeogr., **7**, 27, **1998**.

9. ARMITAGE D. Socio-institutional dynamics and the political ecology of mangrove forest conservation in Central Sulawesi, Indonesia. Global Environ. Chang., **12**, 203, **2002**.

10. PRIMAVERA J.H. Development and conservation of Philippine mangroves: institutional issues. Ecol. Econ., **35**, 91, **2000**.

11. LUGO A.E. Conserving Latin American and Caribbean mangroves: issues and challenges. Madera y Bosques, **8**, 5, **2002**.

12. TOVILLA-HERNANDE C., ESPINO DE LA LANZA G. ORIHUELA-BELMONTE D.E. Impact of logging on a mangrove swamp in South Mexico: cost/benefit analysis. Review Biology Tropical, **49**, 571, **2001**.

13. ELLISON A.M., FARNSWORTH E.J. Anthropogenic disturbance of Caribbean mangrove ecosystems: past impacts, present trends, and future predictions. Biotropica, **28**, 549, **1996**.

14. ELLISON J.C. Wetlands of the Pacific Islands region. Wetlands Ecological Management, **17**, 169, **2009**.

15. COHEN J.E., SMALL C., MELLINGER A., GALLUP J., SACHS J. Estimates of coastal populations. Science, **278**, 1209, **1997**.

16. LUTHER D., GREENBURG R. Mangroves: a global perspective on the evolution and conservation of their terrestrial vertebrates. Bioscience, **59**, 602, **2009**.

17. VALIELA I., JENNIFER L., BOWEN J.K. YORK. Mangrove Forests: One of the World's Threatened Major Tropical Environments. BioScience, **51**, (10), 807, **2001**.

18. ELLISON A.M. Managing mangroves with benthic biodiversity in mind: moving beyond roving banditry. J. Sea Res., **59**, 2, **2008**.

19. FAO. Status and trends in mangrove area extent worldwide. In: Wilkie ML., Fortuna S., Eds. Forest Resources Assessment Working Paper No. 63. Rome: Forest Resources Division, FAO. **2003**. http://www.fao.org/docrep/007/j1533e/j1533e00.HTM. Accessed on 1ˢᵗ May, 2012.

20. MITHTHAPALA S. Mangroves. Coastal Ecosystems Series Vol. 2. Colombo Sri Lanka: Ecosystems and Livelihoods Group Asia IUCN, pp. 28, **2008**.

21. GIESEN W., WULFFRAAT S., ZIEREN M., SCHOLTEN L. Mangrove guidebook for Southeast Asia. FAO and Wetlands International, Bangkok, pp. 796, **2007**.

22. KOMIYAMA A., ONG J.E., POUNGPARN S. Allometry, biomass and productivity of mangrove forests: a review. Aquat. Bot., **89**, (2), 128, **2008**.

23. PUTZ F.E., CHAN H.T. Tree growth, dynamics, and productivity in a mature mangrove forest in Malaysia. Forest Ecol. Manag., **17**, (2-3), 211, **1986**.

24. KOMIYAMA A., MORIYA H., PRAWIROATMODJO S., TOMA T., OGINO K. Forest primary productivity. In: Ogino K., Chihara M. (Eds) Biological System of Mangrove. Ehime University, pp. 97-117, **1988**.

25. NUR ILAYANA MOHD ZUKKI, JUSOFF K. Application of the hierarhical process analysis for precision management of mangrove forests. A poster paper presented at the National Coastal Coastal Zone Management: Togetherness in Action and Alert , 5-7th November 2007. Residence Resort Paka, Terengganu Darul Iman, Malaysia. p. 5, **2007** [In Malay].

26. SPALDING M. D., BLASCO F., FIELD C.D. World Mangrove Atlas. International Society for Mangrove Ecosystems, Okinawa, Japan, pp. 178, **1997**.

27. ONG J. E. Mangroves and aquaculture in Malaysia. Ambio, **11**, (5), 252, **1982**.

28. LUGO A.E., SNEDAKER S.C. The Ecology of Mangroves. Annu. Rev. Ecol. Syst., **5**, 39, **1974**.

29. WALTERS B.B. Patterns of local wood use and cutting of Philippine mangrove forests. Econ. Bot., **59**, (1), 66, **2005**.

30. JUSOFF K., TAHA D. Managing sustainable mangrove forests in Peninsular Malaysia. Journal of Sustainable Development, **1**, (1), 88, **2008**.

31. WAN FARIDAH AKHMAL W. JUSOH, JUSOFF K., ZELINA ZAITON IBRAHIM. Mangrove alertness through kelip-kelip eco-tourism. A poster paper presented at the application of the hierarchical process analysis for precision management of mangrove forests, 5-7th November 2007. Residence Resort Paka, Terengganu Darul Iman, Malaysia. p. 5, **2007** [In Malay].

32. ROBERTSON A., DUKE N.C. Mangroves as nursery sites: comparisons of the abundance and species composition of fish and crustaceans in mangroves and other near shore habitats in tropical Australia. Mar. Biol., **96**, 193, **1987**.

33. JUSOFF K. Geospatial Information Technology for conservation of coastal forest and mangroves environment in Malaysia. Computer & Information Science, **1**, (2), 129, **2008**.

34. CHAUVAUD S., BOUCHON C., MANIÈRE R. Remote sensing techniques adapted to high resolution mapping of tropical coastal marine ecosystems (coral reefs, seagrass beds and mangrove). Int. J. Remote Sens., **19**, (18), 3625, **1998**.

35. SAENGER P., SIDDIQI N.A. Land from the sea: The mangrove afforestation program of Bangladesh, Ocean and Coastal Management, **20**, (1), 23, **1993**.

36. AMJAD A. SHAH, JUSOFF K. Mangrove conservation through community participation in Pakistan: The case of Sonmiani Bay. The 5th WSEAS International Conference on Environment, Ecosystems and Development (EED'07), Puerto De La Cruz, Tenerife, Canary Islands, Spain, pp. 7, December 14-16th, **2007**.

37. FAO. Mangrove forest management guidelines. FAO Forestry Paper 117, Food and Agriculture Organization of the United Nations, Rome, **1994**.

38. FIELD C.D. Rehabilitation of Mangrove Ecosystems: An Overview. Mar. Pollut. Bull., **37**, (8-12), 383, **1998**.

39. TANGAH J., LOHUJI P.L. Management implications of the Sibyte Mangrove Forest Reserve in Sabah based on inventory data. ISME/GLOMIS Electronic Journal, **7**, (2), 3, **2009**.

40. JUNAIDI P., CUBITT G, LAU D. This is Borneo. New Holland Publishers Ltd. ISBN 9781843309635, pp. 176, **2005**.

41. LEWIS R.R. Ecological engineering for successful management and restoration of mangrove forests. Ecol. Eng., **24**, (4), 403, **2005**.

42. LUGO A. E. Old growth mangrove forests in the United States. Conserv. Biol., **11**, (1), 11, **1997**.

43. DUKE N. Mangrove reforestation in Panama. In: Restoration of Mangrove Ecosystems, C. D. Field (Ed). International Society for Mangrove Ecosystems, Okinawa, Japan, pp. 207-232, **1996**.

44. DAVIE J., HYNES R. Integrating nature conservation and sustainable rural management. Australian Biologist, **10**, (4), 185, **1997**.

45. TWILLEY R. R., SNEDAKER S. C., YANEZ-ARANCIBA A., MEDINA E. Biodiversity and ecosystem processes in tropical estuaries: perspectives from mangrove ecosystems. In Biodiversity and Ecosystem Functions: a Global Perspective, (Eds). H. Money, H. Cushman, and E. Medina. Wiley, New York, pp. 327-370. **1996**.

46. CHAN H. T. Mangrove restoration in Peninsular Malaysia. In: Restoration of Mangrove Ecosystems, C. D. Field (Ed.) International Society for Mangrove Ecosystems, Okinawa, Japan, pp. 64-75, **1996**.

47. ROBERTSON A.I., PHILLIPS M.J. Mangroves as filters of shrimp pond effluent: predictions and biogeochemical research needs. Hydrobiologia, **295**, 311, **1995**.

48. WETLANDS INTERNATIONAL ASIA-PACIFIC. Community Participation in Mangrove Forest Management and Rehabilitation in Southern Thailand. 2nd Interim Report (ECU funded project), pp. 26, **1997**.

49. CLOUGH B. F. Primary productivity and growth of mangrove forests. In: Tropical Mangrove Ecosystems, Eds. A. I. Robertson and D. M. Alongi, Coastal and Estuarine Studies 41. American Geophysical Union, Washington, DC. pp. 225-249, **1992**.

50. STEVENSON N. J. Disused shrimp ponds: options for redevelopment of mangrove. Coast. Manage., **25**, (4), 423, **1997**.

51. JAPAN ASSOCIATION FOR MANGROVE. Final report of the ITTO project on development and dissemination of reafforestation Techniques of Mangrove Forests. Publication of JAM, Tokyo, Japan, **216**, 104, **1997**.

52. SMITH T. J. Forest structure. In: Tropical Mangrove Ecosystems, A. I. Robertson and D.M. Alongi (Eds.). Coastal and Estuarine Studies 41, American Geophysical Union, Washington, DC. pp. 101-136, **1992**.

53. HOBBS R. J., NORTON D.A. Towards a conceptual framework for restoration ecology. Restor. Ecol., **4**, (2), 93, **1996**.

54. JAPAN ASSOCIATION FOR MANGROVE. Development and Dissemination of Re-afforestation Techniques of Mangrove Forests. Publication of JAM, Tokyo, Japan, pp. 216, **1994**.

55. UNDERWOOD A. J. Ecological Research and (and Research into) Environmental Management. Ecol. Appl., **5**, 232, **1995**.

56. LAKSHMI M., RAJALAKSHMI S., PARANII M. ANURATHA C. S., PARIDA A Molecular phylogeny of mangroves 1. Use of molecular markers I assessing the intraspeci®c genetic variability in the mangrove species *Acanthus ilicifolius* Linn. (*Acanthaceae*). Theor. Appl. Genet., **94**, (8), 1121, **1997**.

57. PAGLIOSA P.A. The impact of urbanization on biosphere reserves: a comparative study of protected and non-protected coastal areas. Available: http://www.unesco.org.uy/mab/documentospdf/PPAGLIOSA-ABAWARD.pdf. Accessed on 12th December 2012. **2004**.

58. FARNSWORTH E.J., ELLISON A.M. The global conservation status of mangroves. Ambio, **26**, 328, **1997**.

59. DWIVEDI S.N., PADMAKUMAR K.G. Ecology of a mangrove swamp near Juhu Beach, Bombay with reference to sewage pollution. In: TeasHJ, (Ed). Biology and Ecology of Mangrove, TV: S. Vol. 8. Lancaster: Dr W. Junk Publishers. pp. 163-179, **1983**.

60. HUANG L.N., LAN C.Y., SHU W.S. Sewage discharge on soil and plants of the mangrove wetland ecosystem. Chinese Journal of Ecology, 19, 13, **2000** [In Chinese with English abstract].

61. TAM N.F.Y., WONG Y.S. Mangroves sediments as sinks for wastewater-borne pollutants. Hydrobiologia, **295**, 231, **1995**.

62. WONG Y.S., TAM N.F.Y., LAN C.Y. Mangrove wetlands as wastewater treatment facility: a field trial. Hydrobiologia, **352**, 49, **1997**.

63. WANG L., SOUSA W.P., GONG P., BIGING S. Comparison of IKONOS and QuickBird images for mapping mangrove species on the Caribbean coast of Panama. Remote Sens. Environ., **91**, 432, **2004**.

64. DRAKE J.A., MOONEY H.A., DI CASTRI F., GROVES R., KRUGER F., MOONEY H.A., REJ-MANEK M., WILLIAMSON M. Biological Invasions. A Global Perspective. New York, Wiley, **1989**.

65. HIGGINS S.I., RICHARDSON D.M. A review of models of alien plant spread. Ecological Model, **87**, 249, **1996**.

66. QIAN Y.Q., MA K.P. Bio-techniques and bio-safety. Journal of Natural Resource, **10**, 322, **1995**.

67. UPADHYAY V.P., RANJAN R., SINGH J.S. Human-mangrove conflicts: the way out. Current Science, **83**, (11), 1328, **2002**.

68. BARBIER E.B., KOCH E.W., SILLIMAN B.R.,HACKER S.D., WOLANSKI E., PRIMAVERA J., GRANEK E.F., POLASKY S., ASWANI S., CRAMER L.A., STOMS D.M., KENNEDY C.J., BAEL D., KAPPEL C.V., PERILLO G.M.E., REED D. J. Coastal ecosystem based management with non-linear ecological functions and values. Science, **319**, 321, **2008**.

69. DAHDOUH-GUEBAS F., JAYATISSA L.P., DI NITTO D., BOSIRE J.O., SEEN D. L., KOEDAM N. How effective were mangroves as a defence against the recent tsunami? Curr. Biol., **15**, 443, **2005**.

70. AMJAD A. SHAH, KASAWANI I., JUSOFF K. Degradation of Indus Delta mangroves in Pakistan. In: Procs/CD of International Seminar on Wetlands & Sustainability, 4-6 September, 2007, Puteri Pacific Hotel, Johor Bharu, Johor, Malaysia, pp. 347-360. **2007**.

71. POLIDORO B.A., CARPENTER K.E., COLLINS L., DUKE N.C., ELLISON A.M., ELLISON J.C., FARNSWORTH J.E., FERNANDO E.S., KATHIRESAN K., KOEDAM N.E., LIVINGSTONE S.R., MIYAGI T., MOORE G.E., NAM V.N., ONG J.E., PRIMAVERA J.H., SALMO S.G., SANCIANGCO J.C., SUKARDJO S., WANG Y., YONG J.W.H. The Loss of Species: Mangrove Extinction Risk and Geographic Areas of Global Concern. PLoS ONE. **5**, (4), e10095, **2010**.

72. DAS S., VINCENT J.R. Mangroves protected villages and reduce death toll during Indian super cyclone. Proceedings of the National Academy of Sciences, **106**, 7357, **2009**.

73. ABURTO-OROPEZA O., EZCURRA E., DANEMANN G., VALDEZ V. MURRAY J. SALA E. Mangroves in the Gulf of California increase fishery yields. Proceedings of the National Academy of Sciences, **105**, 10456, **2008**.

74. EMERTON L., KEKULANDALA L.D.C.B. Assessment of the economic value of Muthurajawela wetland. Occasional Paper 4. Colombo: IUCN Sri Lanka Country Office, pp. 28, **2002**.

75. EWEL K.C., TWILLEY R.R., JIN E.O. Different kinds of mangrove forests provide different goods and services: biodiversity and function of mangrove ecosystems. Global Ecol. Biogeogr., **7**, (1), 83, **1998**.

76. WALTERS B.B., RONNBACK P., KOVACS J.M., CRONA B., HUSSAIN S.A., BADOLA R., PRIMAVERA J.H., BARBIER E., DAHDOUH-GUEBAS F. Ethnobiology, socio-economic and management of mangrove forests: A review. Aquat. Bot, **89**, 220, **2008**.

77. RÖNNBÄCK P. The ecological basis for economic value of seafood production supported by mangrove ecosystems. Ecol. Econ., **29**, 235, **1999**.

78. LOPEZ-HOFFMAN L., MONROE L.E., NARVAEZ E., MARTINEZ-RAMOS M., ACKERLY D.D. Sustainability of mangrove harvesting: how do harvesters perceptions differ from ecological analysis? Ecological Society, **11**, (2), 14, **2006**.

79. JUSOFF K. UPM-APSB AISA Airborne Hyperspectral Technology for Managing Mangrove Forest in Malaysia. Modern Applied Science, **2**, (6), 90, **2008**.

80. MOHTI A., GODOONG E., JUSOFF K. Mapping of Mangrove forest in the Central Part of Matang Mangrove Forest Reserve Perak Using SPOT-XS Imagery. In: Proceeding of Malaysian Science and Technology Congress: 18-20th September 2000; Promenade Hotel, Kota Kinabalu Sabah, **2000**.

81. JUSOFF K. UPM-APSB's AISA airborne hyperspectral imaging for individual mangrove mapping in Port Klang. In: Procs. National Seminar on Science, Technology & Social Science STSS2006, 30-31st May, 2006, Swiss Garden Resort & Spa, Kuantan, Pahang, Malaysia, pp.751-759, **2006**.

82. JUSOFF K., KASAWANI I. Spectral signatures of some mangrove species in Malaysia. The 5th WSEAS International Conference on Environment, Ecosystems and Development (EED'07), Puerto De La Cruz, Tenerife, Canary Islands, pp. 10, Spain, 14-16th December, **2007**.

83. KASAWANI I., JUSOFF K., NURUN NADHIRAH M.I. A study of forest structure, diversity index and above-ground biomass at Tok Bali Mangrove Forest, Kelantan, Malaysia. The 5th WSEAS International Conference on Environment, Ecosystems and Development (EED'07) Puerto De La Cruz, Tenerife, Canary Islands, pp. 9, Spain, 14 -16th December, **2007**.

84. KASAWANI I., NAJIHA S. AMJAD, JUSOFF K. Wetland cover changes in Kuala Trengganu District using LandsatTM imagery. In: Procs/CD of International Seminar on Wetlands & Sustainability, 4-6th September, 2007, Puteri Pacific Hotel, Johor Bharu, Johor, Malaysia. pp. 111-118, **2007**.

85. HEUMANN B.W. Satellite remote sensing of mangrove forests: Recent advances and future opportunities. Prog. Phys. Geog., **35**, (1), 87, **2011**.

86. HAVEMANN T. Measuring and Monitoring Terrestrial Carbon: The State of the Science and Implications for Policy Makers. The United Nations Collaborative Programme on Reducing Emissions from Deforestation and Forest Degradation in Developing Countries, **2009**.

87. MOHD HASMADI I., PAKHRIAZAD H.Z., JUSOFF K. Mangrove canopy density of Sungai Merbok, Kedah from Landsat TM. J. Malaysian Forester, **71**, (1), 67, **2008**.

88. MOHD HASMADI I., PAKHRIAZAD H.Z., NORLIDA K. Remote sensing for mapping RAMSAR heritage site at Sungai Pulai mangrove forest reserve, Johore, Malaysia. J. Sains Malaysiana, **40**, (2), 83, **2011**.

89. HAMDAN O., KHALI AZIZ H., ABD RAHMAN K. Remotely Sensed L-Band SAR Data for Tropical Forest Biomass Estimation. Journal of Tropical Forest Science, **23**, (3), 318, **2011**.

90. NEUKERMANS G., DAHDOUH-GUEBAS F., KAIRO J.G., KOEDAM N. Mangrove species and stand mapping in Gazi Bay (Kenya) using Quickbird satellite imagery. Journal of Spatial Science, **52**, 75, **2008**.

91. DAHDOUH-GUEBAS F., KOEDAM N. Long-term retrospection on mangrove development using transdisciplinary approaches: A Review. Aquat. Bot, **89**, 80, **2008**.

92. DAHDOUH-GUEBAS F., VAN HIEL E., CHAN J.C-W., JAYATISSA L.P., KOEDAM N. Qualitative distinction of congeneric and introgressive mangrove species in mixed patchy forest assemblages using high spatial resolution remotely sensed imagery (IKONOS). System Biodiversity, **2**, 113, **2005**.

93. KOVACS J.M., WANG J., FLORES-VERDUGO F. Mapping mangrove leaf area index at the species level using IKONOS and LAI-2000 sensors for the Agua Brava Lagoon, Mexican Pacific. Estuar. Coast. Shelf S., **62**, 377, **2005**.

94. GREEN E.P., CLARK C.D., MUMBY P.J., EDWARDS A.J., ELLIS A.C. Remote sensing techniques for mangrove mapping. Int. J. Remote Sens., **5**, 935, **1998**.

95. CLARKE P.J. The population dynamics of the mangrove Avicennia marina: demographic synthesis and predictive modelling. Hydrobiology, **295**, 83, **1995**.

96. IPCC. Guidelines for National Greenhouse Gas inventories. IGES, ISBN 4-88788-032-4, **2006**.

97. MYEONG S., NOWAK D.J., DUGGIN D.J. A temporal analysis of urban forest carbon storage using remote sensing. Remote Sens. Environ., **101**, 277, **2006**.

98. DANIEL C.D., KAUFFMAN J.B., MURDIYARSO D., KURNIANTO S., STIDHAM M. KANNINEN M. Mangroves among the most carbon-rich forests in the tropics. Nature Geoscience Letters. NGEO1123, pp. 5, **2011**.

99. LI X., GAR-ON YEH A., WANG S., LIU K., LIU X., QIAN J., CHEN X. Regression and analytical models for estimating mangrove wetland biomass in South China using Radarsat images. Int. J. Remote Sens., **28**, (24), 5567, **2007**.

100. PROISY C., COUTERON P., FROMARD F. Predicting and mapping mangrove biomass from canopy grain analysis using Fourier-based textural ordination of IKONOS images. Remote Sens. Environ., **109**, 379, **2007**.

101. MOUGIN E., PROISY C., MARTY G., FROMARD F., PUIG H., BETOULLE J.L., RUDANT J.P. Multifrequency and multipolarization radar backscattering from mangrove forests. IEEE T. Geosci. Remote, **37**, 94, **1999**.

102. PROISY C., MOUGIN E., FROMARD F., KARAM M.A. Interpretation of polarimetric radar signatures of mangrove forests. Remote Sens. Environ., **71**, 56, **2000**.

103. PROISY C., MOUGIN E., FROMARD F., TRICHON V., KARAM M. A. On the influence of canopy structure on the polarimetric radar response from mangrove forest. Int. J. Remote Sens., **23**, (20), 4197, **2002**.

104. LUCAS R.M., MITCHELL A.L., ROSENQVIST A., PROISY C., MELIUS A., TICEHURST C. The potential of L-band SAR for quantifying mangrove characteristics and change: Case studies from the tropics. Aquat. Conserv., **17**, 245, **2007**.

105. KAPLOWITZ M.D. Assessing mangrove products and services at the local level: the use of focus groups and individual interviews. Landscape Urban Plan., **56**, (1-2), 53, **2001**.

106. SASEKUMAR A., CHONG V.C. LEH M.U., D'CRUZ R. Mangroves as a habitat for fish and prawns. Hydrobiologia: Fishery Biology and Mariculture, **247**, (1-3), 195, **1992**.

107. ONG J.E. Mangroves – a carbon source and sink. Chemosphere, **27**, (6), 1097, **1993**.

108. CHRISTENSEN B. Management and utilization of mangroves in Asia and the Pacific. FAO Environment Paper No. 3, Food and Agriculture Organization, Rome, **1982**.

109. HAMILTON L.S., J.A. DIXON MILLER G.O. Mangrove forests: an undervalued resource of the land and of the sea. In: E.M Borgese, N. Ginsburg and J.R. Morgan, eds. Ocean Yearbook 8. University of Chicago Press, Chicago. pp. 254-288, **1989**.

110. JARA R.S. Traditional uses of the mangrove in the Philippines. In CD: Field and A.J. Dartnall, (Eds). Mangrove Ecosystems of Asia and the Pacific: Status, Exploitation and Management. Australian Development Assistance Bureau and Australian Committee for Mangrove Research, Townsville. pp. 114-130, **1987**.

111. KUNSTADTER P., BIRD E.C.F., SABHASRI S. Man in the mangroves. United Nations University, Tokyo, **1986**.

112. LACERDA L.D. Conservation and sustainable utilization of mangrove forests in Latin America and African regions (Part 1: Latin America). Mangrove Ecosystem Technical Reports 2, International Society for Mangrove Ecosystems and International Tropical Timber Organization, Tokyo, **1993**.

113. GATTENLÖHNER U., LAMPERT S., WUNDERLICH K. Mangrove Rehabilitation Guidebook. Published in the framework of the EU-ASIA PRO ECO II B Post Tsunami Project in Sri Lanka. Global Nature Fund. http://www.globalnature. org/bausteine.net/file/showfile.aspx?downdaid=6426&domid =1011&fd=2. 2007. Accessed on 19th November, **2012**.

114. NAYAK A. K. Post Super Cyclone Orissa: An Overview http://orissa.gov.in/e-magazine/Orissareview/2009/ October/engpdf/Pages98-104.pdf. Orisa Review, October, pp.98-104, 2009. Accessed on 31st January **2013**.

115. KOH H. L., TEH S. Y., LIU P. L.-F., IZANI A. M. I., LEE H. L. Simulation of Andaman 2004 Tsunami for Assessing Impact on Malaysia. J. Asian Earth Sci., **36**, (1), 74, **2009**.

116. KOH H.L., S.Y. TEH T. A., MAJID T.K. LAU AHMAD F. Earthquake and Tsunami Research in USM: The Role of Disaster Research Nexus. Pertanika J. Science. & Technology, **20**, (1), 151, **2012**.

117. MAZDA Y., MAGI M., KOGO M., HONG P.N. Mangrove on coastal protection from waves in the Tong King Delta, Vietnam. Mangroves and Salt Marshes, **1**, 127, **1997**.

118. MAZDA Y., WOLANSKI E., KING B., SASE A. OHTSUKA D., Drag force due to vegetation in mangrove swamps. Mangroves and Salt Marshes, **1**, (3), 193, **1997**.

119. HARADA K., IMAMURA F., HIRAISHI T. Experimental study on the effect in reducing Tsunami by the coastal permeable structures. Final Proc. Int. Offshore Polar Eng. Conf., USA, pp. 652-658, **2002**.

120. HIRAISHI T., HARADA K. Green belt Tsunami Prevention in South-Pacific Region. http://eqtap.edm.bosai.go.jp/ useful_outputs/report/hiraish/data/ papers/greenbelt.pdf. 2013. Accessed on 31st January **2013**.

121. MASSEL S.R. Tides and waves in mangrove forests: in fluid mechanics for marine ecologists. Springer-Verlag, pp. 418-425, **1999**.

122. KATHIRESAN K., RAJENDRAN N. Coastal mangrove forests mitigated tsunami. Estuar. Coast. Shelf S., **65**, 601, **2005**.

123. BANDARANAYAKE W.M. Traditional and medicinal uses of mangroves. Mangroves and Salt Marshes, **2**, (3), 133, **1998**.

124. TANAKA K., POH S.C. Influences of Nutrient Outwelling from the Mangrove Swamp on the Distribution of Phytoplankton in the Matang Mangrove Estuary, Malaysia. Journal of Oceanography, **56**, (1), 69, **2000**.

125. SANFORD M.P. Valuating Mangrove Ecosystems as Coastal Protection in Post-Tsunami South Asia. Nat. Area J., **29**, (1), 91, **2009**.

126. SATHIRATHAI S., BARBIER E.B. Valuing Mangrove Conservation In Southern Thailand. Contemp. Econ. Policy, **19**, (2), 109, **2001**.

127. SHERIDAN P., HAYS C. Are mangroves nursery habitat for transient fishes and decapods? Wetlands, **23**, (2), 449, **2003**.

128. FEAGIN R.A., MUKHERJEE N., SHANKER K., BAIRD A.H., CINNER J., KERR A.M., KOEDAM N., SRIDHAR A., ARTHUR R., JAYATISSA L.P., SEEN D.L., MENON M., RODRIGUEZ S., SHAMSUDDOHA M., GUEBAS F.D.. Shelter from the storm? Use and misuse of coastal vegetation bioshields for managing natural disasters. Conservation Letters. **3**, (1), 1, **2009**.

129. LIN P., FAN H.Q. Seasonal model of the decomposition rates of *Kandelia candel* fallen leaves in Jiulongjiang River estuary. J Xiamen Univ (Nat Sci), **31**, 430, **1992** [In Chinese with English abstract].

130. LEE S.Y. Primary productivity and particulate organic matter flow in an estuarine mangrove wetland in Hong Kong. Mar. Biol, **106**, 453, **1990**.

131. FAN H.Q., LIN P. Potential role of leaching in weight loss during the decomposition of mangrove *Kandelia candel* leaf litter. Oceanol Limnol Sin. **26**, 28, **1995** [In Chinese with English abstract].

132. YIN Y., LIN P. Study on the litter fall of *Rhizophora stylosa* community in Yinluo Bay, Guangxi. Guihaia, **12**, 359, **1992** [In Chinese with English abstract].

133. LIN Q.R. Damage and management of Spartina anglica and *Spartina alterniflora*. Fujian Geography, **12**, 16, **1997**.

134. LU C.Y., WONG Y.S., TAM N.F.Y. YE Y., LIN P. Methane flux and production from sediments of a mangrove wetland on Hainan Island, China. Mangroves Salt Marshes. **3**, 41, **1999**.

135. YE Y., LU C.Y., WONG Y.S., TAM N.F.Y., LIN P. CUI S., YANG S. LI L. Methane fluxes from sediments of *Bruguiera sexangula* mangroves during different diuranal periods and in different flat zones. J Xiamen Univ (Nat Sci), **36**, 925, **1997** [In Chinese with English abstract].

136. YE Y., TAM N.F.Y., WONG Y.S., LU C.Y. Growth and physiological responses of two mangrove species (*Bruguiera gymnorrhiza* and *Kandelia candel*) to waterlogging. Environmental Experimental Botany, **49**, 209, **2003**.

137. YE Y., TAM N.F.Y., WONG Y.S. Does sea level rise influence propagule establishment, early growth and physiology of *Kandelia candel* and *Bruguiera gymnorrhiza*? Journal Experimental Marine Biology Ecology, **306**, 197, **2004**.

138. TAM N.F.Y., WONG Y.S. Accumulation and distribution of heavy metals in a simulated mangrove system treated with sewage. Hydrobiologia, **352**, 67, **1997**.

139. GILMAN E., ELLISON J., COLEMAN R. Assessment of mangrove response to projected relative sea-level rise and recent historical reconstruction of shoreline position. Environ. Monit. Assess., **124**, 105, **2007**.