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Mangroves: Ecology, Biodiversity and Management

Springer

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Preface

Mangroves are one of the most productive and biologically important blue-carbon ecosystems across the coastal intertidal zone, on the planet Earth. It develops very differently in various ecological settings; however, the expansion of mangroves is commonly found along the tropical and subtropical coastlines around the world. In the current scenario of serious environmental issues of global warming and climate change, mangrove forests may play a vital role in mitigating the rising greenhouse gas emissions due to their extreme capacity in carbon sequestration per unit area. It has been estimated that mangrove forests can store about four to five times more carbon than terrestrial rainforests. Moreover, mangroves play a key role in mitigating global climate change and defend against extreme natural disasters, such as onslaught of cyclones, floods, winds and tidal surges, to the human settlements along the coastal ecosystems.

Various flora and fauna inhabiting mangrove ecosystems have developed several discrete adaptations to withstand daily fluctuating environment with changes in salinity, water and oxygen content with the rise and fall of the sea-tide. Moreover, mangroves are rich in biological diversity of different taxonomic groups with great ecological and commercial importance. Mangroves yield large amounts of oysters, fish, prawns, crabs, fuel-wood, timbers, tannins and other natural products.

Owing to the utmost ecological as well as the economic importance of mangroves, their restoration and proper management are crucial. However, increasing anthropogenic activities and global climate change have raised worldwide concerns towards the conservation, survival and productivity of mangrove ecosystems. Therefore, effective conservation strategies and solid management action plan should be implemented at the global level for their sustainable use, ecological balance and development as a unique ecosystem intended for livelihood and healthy environment.

The proposed book will emphasize the emerging information on ecology of mangroves, with a special reference to their biodiversity and management.

This book has attempted to span the depth of mangrove's ecology starting with more general information such as types, importance and biogeography of the mangrove ecosystem in Chaps. 1 and 2. Mangrove is an important habitat for fauna, in relation to food availability, and as a nursery for several species during different stages of their life cycles, which has been discussed in Chap. 3 as feeding and breeding grounds of mangroves. Chapter 4 focuses on diverse environmental factors influencing the mangrove ecosystems. Chapter 5 highlights the energy flux in a mangrove ecosystem, which will help to understand the energy balance in a mangrove ecosystem. The information regarding nitrogen and phosphorus budget in mangrove ecosystems by exploring the storage, transformation and fluxes in mangrove sediment, biomass, atmosphere and tidal waters has been discussed in Chap. 6. Determination of carbon sinks and estimation of blue-carbon stock of mangrove ecosystem have been reviewed in Chaps. 7 and 8. Chapters 9 and 10 address the responses of mangroves to climate change in the Anthropocene and deep insight of mangroves in combating climate change, respectively. Chapter 11 describes the role of mangroves in pollution abatement. Chapter 12 presents the measurement and modelling of above-ground root systems as attributes of flow and wave attenuation function of mangroves. Chapter 13 explains the roles of mangrove as natural barrier to environmental risks and coastal protection. Chapters 14 and 15 all deal with structure and diversity of polychaetes in mangroves of the Indian coast, as well as structure, composition and diversity of plants in mangrove ecosystems in different locations of the world, respectively. Chapter 16 deals with the patters of livelihood of forest dependent dwellers in relation to the exploitation of resources at the fringe of Indian Sundarbans. The role of mangroves in sustainable tourism development and conserving it for future generations has been mentioned in Chap. 17. In Chap. 18, the role of mangroves in supporting the aquaculture industries has been discussed. Chapters 19 and 20 highlight the ecological valuation and ecosystems of mangroves along with the development of effective management action plans to promote the sustainability of mangrove forest reserves, respectively. Chapter 21 presents an overview of how the RS and GIS technologies are evolving in the context of their use for scientific and quantitative studies on mangroves.

I believe that this book will be helpful to a great extent for the academicians and researchers in the field of mangroves. Undoubtedly, the contents incorporated in this book can be used as a textbook by undergraduate and postgraduate students, teachers and researchers in the fields of mangroves ecology, biodiversity and management.

I thank Ms. Aakanksha Tyagi, Senior editor (Books), Springer Nature for her assistance in seeing it through to completion. I am sincerely grateful to the entire team of Springer for the coordination, support and implementation of this book project. Last but not least, I express my sincere gratitude to all the authors for their kind collaboration and scientific contributions towards the completion of this book, successfully.

New Delhi, India — Rajesh P. Rastogi
New Delhi, India — Mahendra Phulwaria
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Mangroves: Types and Importance

1

K. Kathiresan

Abstract

Mangroves are of great ecological significance and economic importance. They are of different types—deltaic, estuarine, lagoon, and fringe mangroves—based on coastal location. The mangroves are of six functional types—fringe, riverine, basin, over-wash, scrub, and hammock. They are also of three types—river-dominated, tide-dominated, and interior mangroves—based on tidal range and sedimentation. In addition, there are six broad types of mangroves: large deltaic systems, tidal plains, composite plains, fringing barriers with lagoons, drowned bedrock valleys, and coral coasts. Mangroves are ecologically significant in protecting the coast from solar UV-B radiation, 'greenhouse' gases, cyclones, floods, sea level rise, wave action, and coastal soil erosion. They act as nutrient sinks, sediment traps, and nutrient source to support the food web in other coastal ecosystems. The mangroves are the most efficient in carbon sequestration and climate change mitigation. They provide feeding, breeding, and nursery grounds for many food fishes and wildlife animals. They protect other marine systems such as islands, coral reefs, seaweeds, and seagrass meadows. Mangroves are economically valuable in supplying the forestry and fishery products and also in serving as sites for developing a burgeoning eco-tourism. The mangroves are of great bioprospecting potential as a source of salt-tolerant genes, chemicals, and valuable products that can be used in medical, industrial, agricultural, and food sectors.

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Keywords

Mangroves · Ecological role · Economic value · Bioprospecting · Coastal ecosystems

1.1 Introduction

Mangroves are highly productive and biologically diverse coastal habitats of tropical and subtropical regions of the world. They are the one place on earth where land, freshwater, and ocean mix. They are found in intertidal areas along sheltered shores and estuaries. The mangroves have diversified habitats, such as water bodies, forests, litter forest floor, mudflats and adjacent coral reefs and seagrass meadows; and this habitat diversity supports a wide variety of organisms. The mangrove habitats are chiefly colonized by flowering trees and shrubs, remarkably adapted to harsh coastal conditions, such as seawater, periodic inundation and exposure, wind, waves, strong currents, and anaerobic soil. There are no other groups of plants in the entire plant kingdom with such highly developed adaptations. The 'standing crop' of mangroves is greater than any other aquatic ecosystems on the earth (Duke et al. 1998; Kathiresan and Bingham 2001; Kathiresan and Qasim 2005; Spalding et al. 2010; Tomlinson 2016).

Mangroves occur in low-lying coastal plains where the topography is smooth, but not steep and the tidal amplitude is large. They have luxuriant growth in the alluvial soil substrates with fine-textured loose mud or silt, rich in humus. The mangrove plants find difficult to colonize the coastal zone with waves of high energy, and hence they normally establish themselves in sheltered shorelines (Kathiresan and Bingham 2001; Kathiresan and Qasim 2005).

Mangroves are the only tall tree forest system, located between land and sea in tropical and subtropical coasts. They are a rare forest type in the world with 80 tree and shrub species, occupying 13.8 million hectares in 118 countries and territories (Giri et al. 2011; Duke 2017). They are largely restricted to the latitudes between 32° N and 38° S. Growth and biomass production of the mangroves decrease with increasing latitudes and they are the highest around the equator region. The mangroves are often called as 'tidal forests', 'coastal woodlands', 'oceanic rain-forests' or 'blue carbon forest'. Unfortunately, long-term survival of the mangroves is at a great risk, and the ecosystem services offered by them may totally be lost in the world within the next 100 years (Duke et al. 2007). The present chapter deals with different types of mangroves, ecological significance, and economic importance, for better conservation and management.

1.2 Types of Mangroves

Mangroves and their environment are strongly interacting with each other. The mangroves influence chemical and physical conditions of their environment, which in turn influence growth and productivity of the mangroves. They are found

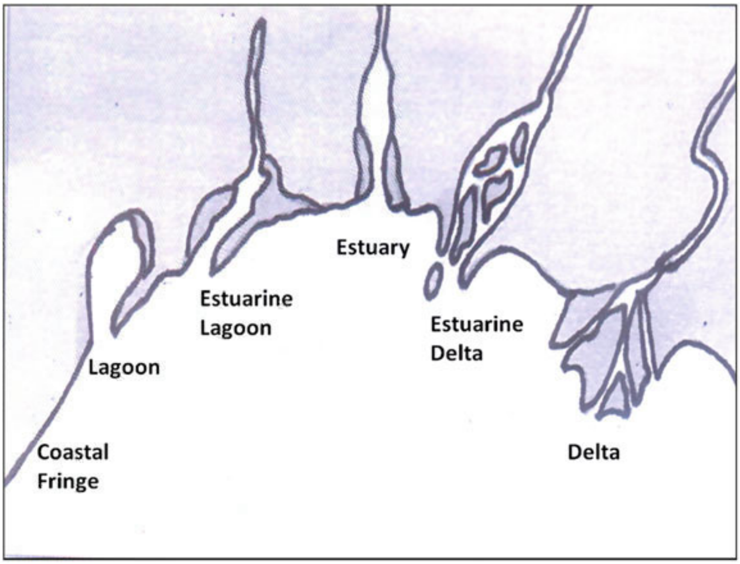

Fig. 1.1 Tropical coastal settings of mangrove forests

in a variety of tropical coastal settings such as the deltas, estuarine deltas, estuaries, estuarine lagoons, lagoons, and coastal fringes (Fig. 1.1) (Kjefve 1990). The deltas are formed by active deposition of sediment at the river mouth, which is colonized by mangroves. Estuaries are the sites of sediment deposition, which is colonized by mangroves. Coastal lagoons are formed behind sand spits and barrier islands; these sites are of less wave action and colonized by mangroves. Mangroves do occur on sediment substrates along the coastal fringes where wave energy is low.

There are six functional types of mangrove forests as shown in Fig. 1.2, namely, over-wash, fringe, riverine, basin, scrub (dwarf), and hammock forests (Lugo and Snedaker 1974; Woodroffe 1992). The last three types are the modified forms of the first three types. The six types can be summarized as follows:

1. **Over-wash mangrove forests**: These are small mangrove islands, frequently formed by tidal washings.
2. **Fringe mangrove forests**: These occur along the borders of protected shorelines and islands, influenced by daily tidal range. They are sensitive to erosion and long exposure to turbulent waves and tides.
3. **Riverine mangrove forests**: These are luxuriant patches of mangroves existing along rivers and creeks, which get flooded daily by the tides. Such forests are influenced by large amounts of freshwater and nutrients and thus making the system highly productive with tall trees.
4. **Basin mangrove forests**: These are stunted mangroves located along the interior side of the swamps and in drainage depressions.

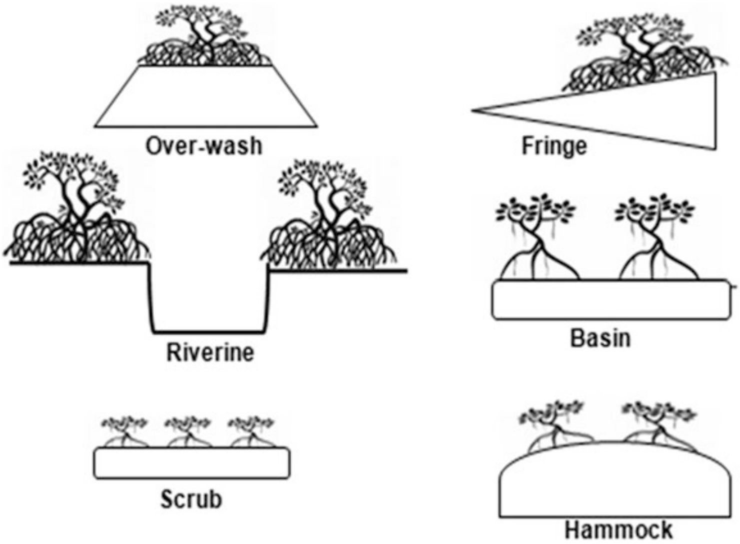

Fig. 1.2 Six functional types of mangrove forests

5. **Hammock mangrove forests**: These are similar to the basin type but occurring in more elevated sites than the four types given-above.
6. **Scrub mangroves**: These are dwarf mangrove forests occurring along flat coastal fringes.

The above classification is not providing any information on the physical processes that take place in mangrove forests. Considering the physical processes, another classification has been proposed with three types of mangrove forests: (1) river-dominated, (2) tide-dominated, and (3) interior mangrove forests (that have less influence of river/or tides) (Fig. 1.3) (Woodroffe 1992). The river-dominated mangroves have a strong out-welling, whereas the tide-dominated mangroves have bidirectional flux, and while the mangroves that are located in interior region are typical sinks for sediment nutrients.

There are six broad classes of mangrove settings, based on the tidal range and sedimentation:

1. **Large deltaic systems** (occurring in low tidal range and substrate with very fine sediments) (e.g. mangroves of Borneo, Sundarbans).
2. **Tidal plains** (where large mudflats are formed by alluvial sediments, reworked by tides, and then the mudflats are colonized by mangroves).
3. **Composite plains** (influenced by both tidal and alluvial conditions, e.g. lagoons formed behind wave-built barriers where mangroves grow).
4. **Fringing barriers with lagoons** (high wave energy conditions with sediments of fine sand and mud) (e.g. mangroves of the Philippines)

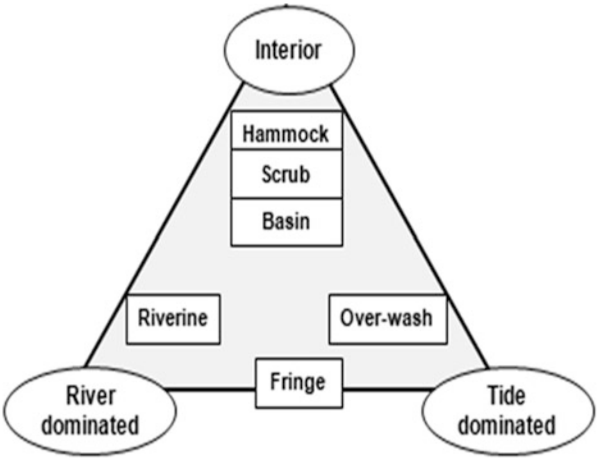

Fig. 1.3 Three Major types of mangrove forests

5. **Drowned bedrock valleys** (e.g. mangroves of Northern Vietnam or Eastern Malaysia)
6. **Coral coasts** (mangroves growing at the bottom of coral sand or in platform reefs) (e.g. mangroves of Indonesia, and Singapore).

Based on global distribution, the mangroves are of two types: 'Old world mangroves' and 'New world mangroves'. The 'Old world mangroves' is the place of origin for mangroves in the Eastern hemisphere, whereas the 'New world mangroves' is the place of relatively recent origin for mangroves in the Western hemisphere. The Eastern hemisphere is Indo-West Pacific region that includes East Africa, Indo-Malaysia, and Australasia. The Western hemisphere is Atlantic East Pacific region that includes West America, East America, and West Africa. Thus, there are six geographic regions of global mangroves in the world. The Eastern hemisphere has 57% of global mangrove area, while Western hemisphere has 43%. The Eastern hemisphere is rich in biodiversity with 63 mangrove species, while the Western hemisphere is poor in biodiversity with only 19 species. Mangroves have broader ranges along the warmer eastern coastlines of the Americas and Africa than along the cooler western coastlines (Fig. 1.4). This difference in distribution is attributed to the presence of warm and cold oceanic currents (Duke 1992).

Global mangrove habitats are inhabited by 80 tree and shrub species including 69 species and 11 hybrids, belonging to 32 genera under 17 families worldwide. Except one genus all the other genera are flowering plants (Tomlinson 2016; Duke et al. 1998; Duke 2017). Mangrove diversity is the highest around South East Asia in the old world mangroves. Some mangrove genera are specific to some regions: *Pelliciera*, *Conocarpus*, and *Laguncularia* are present only in the new world, whereas *Osbornia* and *Camptostemon* exist only in the old world. The mangrove fern *Acrostichum aureum* is the only species, common to both the new and old worlds. In the world, there are two places, richest in mangrove genetic diversity, and these are the Bhitarkanika (Odisha) in India and the Baimuru in Papua New Guinea.

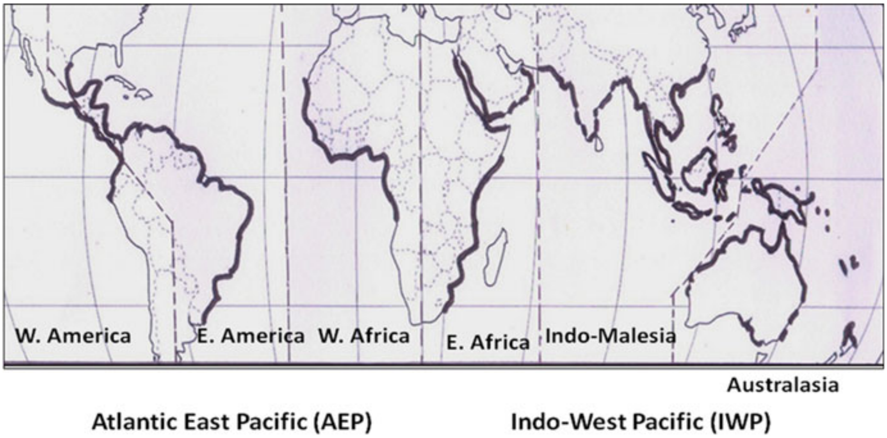

Fig. 1.4 Global distribution of mangroves with six geographic regions

Among the countries, Indonesia has the largest extent of mangrove cover. Sundarbans is the largest single block of mangrove forest in the world, and the second largest ones are in Niger Delta, northern Brazil, and southern Papua.

1.3 Mangrove Ecosystem Services

1.3.1 Protecting from Intense Sunlight and UV-Radiation

Mangroves are able to grow under intense sunlight and solar UV-B radiation. *Avicennia marina* grows under hot and arid conditions with high sunlight, while *Rhizophora* species are quite tolerant to solar UV-B radiation. The mangroves are rich in phenolic compounds that dissipate the excessive sunlight. The flavonoids accumulated in the mangrove leaves serve as UV-screen compounds. Hence, the mangroves are free from the deleterious effects of heat energy and UV-B radiation under-canopy environment (Moorthy and Kathiresan 1997a, b).

1.3.2 Reducing 'Greenhouse Gas' and Carbon Sequestration

The coastal vegetated habitats such as mangroves, salt marshes, and seagrasses are considered to be 'blue carbon ecosystems'. They are amongst the most significant carbon reservoir in the biosphere, and they play a great role in oceanic carbon cycle. The annual carbon burial by coastal vegetated habitats is 180 times greater than that in the deep sea sediments. The vegetated coastal habitats cover only less than 0.2% of the seafloor, but they contribute about 50% of the global burial of organic carbon in marine sediments (Duarte et al. 2005).

Among blue carbon ecosystems, the mangroves are efficient in removing atmospheric CO_2 through photosynthesis, and storing carbon in their biomass and soil substrates. By area, mangrove forests constitute only 0.1% of the world's plant biomes and only 0.7% of the global coastal zone, yet they contribute to the global carbon in a larger way. Mangrove net primary production equals 10% of total net primary production in the coastal zone (Alongi 2007).

Mangroves are the only blue carbon forest of the world. The mangrove forests account for only 1% (13.5 Gt.year^{-1}) of carbon sequestration by the world's forests, but they account for 14% of carbon sequestration by the global ocean (Alongi 2012). They supply more than 10% of the organic carbon, essential to the world oceans (Dittmar et al. 2006). Hence, the mangroves reduce the problems of 'greenhouse gases' and global warming (Kathiresan and Bingham 2001).

Mangrove forests are globally significant carbon sinks, storing carbon in a range of 455–856 mega-gram in one hectare of forest and 6.2–11.7 peta-gram in the world (Alongi 2020; Kauffman et al. 2020; Ouyang and Lee 2020). They are 10 times greater in carbon sequestration and four times efficient in carbon stocks than other tropical forests (McLeod et al. 2011). The mangroves also have larger carbon stock in tropics (895 $\pm$ 90 MgC ha^{-1}) than sub-tropics (547 $\pm$ 66 MgC ha^{-1}) (Sanders et al. 2016). The mangrove forests hold higher carbon stock in Asia-Pacific (1094 MgC ha^{-1}) than other regions: Latin America (939 MgC ha^{-1}), West Central Africa (799 MgC ha^{-1}), and Arabian/Oman Gulf (217 MgC ha^{-1}) (Kauffman and Bhomia 2017).

Mangroves are highly productive, storing large amounts of carbon in their soil system over a very long period of time due to high sedimentation rates and anoxic soils (Donato et al. 2011; Atwood et al. 2017; Alongi 2018) in contrast to other forest soils that store carbon only for a short time. The mangrove soil is reported to account for 76.5% of total carbon in ecosystem (Alongi 2014, 2020) and to store carbon in a range of 2.6–6.4 PgC in the top one metre of soil in the global mangroves (Jardine and Siikamaki 2014; Atwood et al. 2017; Sanderman et al. 2018). The mangrove soil is more efficient in carbon burial by 2.4-folds than salt marshes, by 5.2-folds than seagrasses, and by four-fold than in tropical forests (Duarte et al. 2005). In addition, mangrove root biomass is higher than other forest types. The biomass invested in mangrove roots is 40% of shoot, in contrast to 25% in upland forests. This higher root biomass helps to ensure stability in the soft substrates of mangrove environment.

Mangroves have high carbon sequestration, which is estimated to be 14.2 TgC. year^{-1} and the value per unit area is 1.71 $\pm$ 0.17 MgC ha^{-1} year^{-1} for global mangroves (Alongi 2018). The Indian Sundarbans has the capacity to sequester a total of 2.79 TgC in its natural forest area of 4264 km^2 (Ray and Jana 2017). The carbon sequestration is high at early stage of the forest. A 20-year old plantation of mangroves stores 11.6 kg m^{-2} of carbon with C burial rate of 580 g m^{-2} year^{-1} in Japan (Fujimoto 2000). In Malaysia, a 20 year old stand of *Rhizophora apiculata* mangrove forest is reported to store 7.14 MgC ha^{-1} year^{-1}. The rate of carbon sequestered in mangrove mud is estimated to be 1.5 MgC ha^{-1} year^{-1}. Each hectare of mangrove sediment contains 700 Mg carbon per metre depth (Ong 1993; Ong et al. 1995). However, species-wise variations do occur. *Avicennia marina* performs better to display 75% higher rate of carbon sequestration than that in *Rhizophora mucronata* (Kathiresan et al. 2013a). Total carbon is 98.2% higher in natural mangroves and 41.8% in planted mangroves than that in non-mangrove soil (Kathiresan et al. 2014).

Mangrove loss disturbs the carbon stocks resulting in emission of greenhouse gas (Alongi 2012). A loss of about 35% of the world's mangroves has resulted in a net loss of 3.8×10^{14}g C stored as mangrove biomass (Cebrain 2002). Mangrove deforestation in the world generates emissions of 0.02–0.12 pico grams of carbon per year. This is as much as around 10% of emissions from global deforestation of all forests (Spalding et al. 2010). Carbon storage is reduced in disturbed mangroves than that in intact mangroves: by four folds lower in degraded or deforested forests, three folds lower in the forests, impacted by domestic or aquaculture effluents, and two folds lower in the forests, affected by storms and flood (Perez et al. 2018). Thus failing to preserve mangrove forests can cause considerable carbon emissions and thus global warming. Therefore, mangrove restoration can be a novel countermeasure for global warming issue.

1.3.3 Protecting from Cyclone and Storms

Mangrove forests save the coastal people against cyclones and storms. The 'supercyclone' that occurred on the 29th October 1999 with a wind speed of 310 km/h along the Odisha coast in India caused heavy damage in the coastal area that was devoid of mangroves. But, there was practically no damage occurred in the coastal areas with dense mangrove forest. This super-cyclone killed over 10,000 people and caused a heavy loss of livestock and property. This loss would have been avoided, had the mangrove forests been intact. The protection value of one hectare of intact mangroves is reported to be 8700 US dollars, as against the value of 5000 US dollars fetched for one hectare of cleared land. Yet another example is the cyclone 'Nargis' that hit the coast of Myanmar on the third May, 2008 killed over 30,000 people and heavy loss of properties only in the areas that were devoid of mangroves. The beneficial effect of mangroves was also recorded during the cyclones especially 'Aila'—2009, 'Ockhi'—2017, 'Gaja'—2018 along the east coast of India. The mangroves act as a defence force against natural calamity and hence protecting mangroves as storm buffers generates more value to society.

1.3.4 Protecting from Giant Waves

Mangrove forests protect the coast against strong wave actions. This was evident during the 26th December 2004 tsunami that occurred in the Indian Ocean area, which killed 3 million people in Asian and African countries and caused a loss of 6 billion US dollars in 13 countries. However, mangroves mitigated the deleterious impact of the tsunami waves and protected the shoreline against damage (Kathiresan

Fig. 1.5 The 2004 tsunami broken a long boat jetty in to pieces, while mangroves intact without damage in Parangipettai, south east India

and Rajendran 2005; Danielsen et al. 2005). However, the 2004 tsunami affected mangroves in some places, especially in Andaman and Nicobar Islands. In Andaman, the tsunami caused considerable change in the mangrove stands of the islands; where *Avicennia marina* and *Sonneratia alba* were not generally affected, while *Rhizophora* species got affected due to continuous submergence by seawater as a result of the tsunami waves. In South Andaman, 30–80% of mangrove stands got affected due to natural elevation of land; however, in middle Andaman and North Andaman, mangroves were not affected (Dam Roy and Krishnan 2005; Ramachandran et al. 2005).

The role of mangroves in reducing the sea-waves is well-known. A hydraulic experiment has proved that mangroves are more effective for reduction of wave damages than concrete seawall structures such as wave dissipating block, breakwater rock, and houses (Harada et al. 2002) (Fig. 1.5). Another study has proved that six-year-old mangrove forest of 1.5 km width reduces the sea-waves by 20 times, from 1 m high waves at the open sea to 0.05 m at the coast (Mazda et al. 1997). The reduction of wave amplitude and energy by tree vegetation has also been proved by measurements of wave forces and modeling of fluid dynamics (Massel et al. 1999). According to an analytical model, 30 trees from 10 m^2 in a 100 m wide belt can reduce the maximum tsunami flow pressure by more than 90%, if the wave height is less than 4–5 m (Hiraishi and Harada 2003). As per our observation, the mangroves can provide protection against tsunami in the situation, where the height of mangrove forest (with >25 trees/10 m^2) is higher than the tsunami wave height (Kathiresan and Rajendran 2005). Therefore, conserving or restoring mangroves will save the coast from future events of natural disasters such as tsunami.

1.3.5 Controlling Flood Damage

Mangroves protect coastal systems against floods that are often caused by tidal waves or heavy rainfall in association with storms. The mangroves are able to control the flood due to the root system, which has a larger spread out area and also ability to promote sedimentation.

Global mangroves provide flood protection benefits exceeding 65 billion US dollars per year. If mangroves were lost, annually 15 million more people would be affected by flood across the world. The greatest economic benefits are recorded with USA, China, India, and Mexico. The economic benefits in terms of people protected are found in Vietnam, India, and Bangladesh. Many 20-km coastal stretches receive more than 250 million US dollars annually in flood protection benefits from mangroves (Pelayo et al. 2020). The mangroves protect more than 150,000 people from flooding every year in Abidjan and Lagos in West Africa, Mumbai and Karachi in South Asia, Wenzhou in East Asia, and Cebu and Denpasar in South east Asia. The mangroves provide annually over 500 million US dollars in avoiding the property loss in cities such as Miami in the USA and Cancun in Mexico. However, the mangroves are beneficial not only to urban areas but also to less populated coastal floodplains (Pelayo et al. 2020).

Besides flood control, the mangroves do prevent the entry of seawater inland and protect the underground water systems, which are a source of drinking water supply to coastal population (Kathiresan 2018). In addition, the mangroves reduce the salinity of the groundwater. This is evident by the fact that there is a very sharp decline in salt concentrations of groundwater at the interface between salt flats and mangroves (Ridd and Sam 1996).

1.3.6 Preventing Coastal Soil Erosion

Mangroves reduce the wave action and prevent the coastal erosion. The reduction of waves increases with density of vegetation. In a tall mangrove forest, the rate of wave reduction is as large as 20% in a distance of 100 metre (Mazda et al. 1997). Mangrove forests are ‘live seawall’-like natural formations and are very cost-effective as compared to the concrete seawall and other structures for coastal protection against erosion (Harada et al. 2002). The mangrove forest with 100 m width is proved to protect the sea dyke, lying behind the forest, for more than 50 years, in contrast to rock fencing that protects the sea dyke for only 5 years. This is because of the fact that the rock fencing is not long resistant to wave damage as compared to mangrove forest, as proved in the Red River Delta, Vietnam. The cost of mangrove planting is 1.1 million US dollars, but it has helped to avoid the maintenance cost of 7.3 million US dollars per year for the sea dyke. However, mangrove deforestation causes coastal erosion, as proved in the Gulf of Kachchh and other regions (World Disaster Report 2002).

1.3.7 Trapping Coastal Sediments

Mangroves are capable of trapping sediment, and thus acting as sinks for the suspended sediments (Woodroffe 1992; Wolanski et al. 1992; Wolanski 1995; Furukawa et al. 1997). The mangroves catch sediments by their complex aerial root systems and thus they function as land expanders. Generally annual sedimentation rate ranges between 1 and 8 mm, in the mangrove areas (Bird and Barson 1977). A contrary view is also proposed that the mangrove forests are the result, and not the cause of sedimentation in coastal areas, but they accelerate the sedimentation process. This depends largely on the exchange process taking place between mangroves and the adjoining coastal areas (Woodroffe 1992).

The mechanism of sediment trapping in mangrove habitats is shown in Fig. 1.6 (Furukawa et al. 1997; Kathiresan 2003). The mangroves inhibit tidal flows, due to the friction force that is provided by the trees with complex aerial root structures. The soil particles are carried in suspension by the incoming tide, whereas the soil particles are left behind in the mangrove swamps by the outgoing tides. Thus, the particles settle down in the forests during the low tide, when the turbulence gets reduced and the water velocity becomes low and sluggish to carry the soil particles back to the sea. In contrast, the particles are held in suspension during the high tide, when the turbulence is high.

Density of mangrove species and their complexity of root systems are the most important factors that determine the sedimentation process (Kathiresan 2003). The sedimentary process also varies in different types of mangrove forests: riverine, basin, and fringe types. The process falls in decreasing order: Riverine > basin > fringe (Ewel et al. 1998). The river-dominated system receives

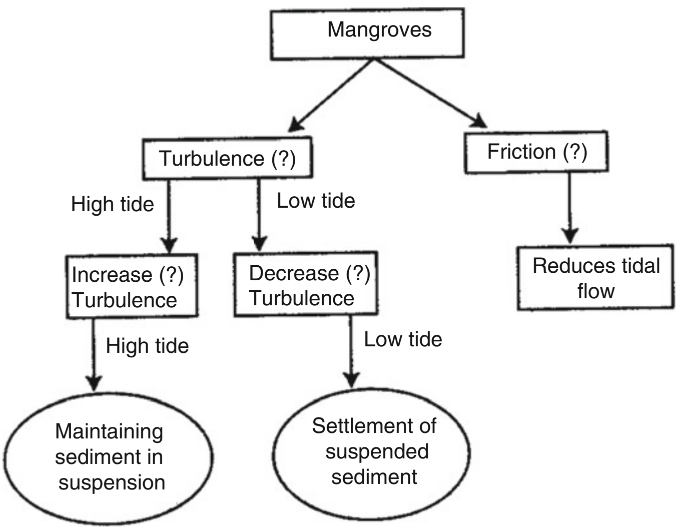

Fig. 1.6 Mechanism of sedimentation as induced by mangroves

sediment supply from the upland areas. The tide-dominated fringe system contains abundant sediment from the sea, but the sedimentation gets disturbed by the tides. The interior basin mangroves are the sinks for sediments (Woodroffe 1992).

1.3.8 Deepening of Creeks

Water circulation through mangrove forests is important for keeping creeks deeper. The water movement in tidal creek is different from surrounding mangrove swamps. This is because of the fact that the tidal creek is deep, while the mangrove swamp is a shallow system, colonized with vegetation. The cause of water movement is the tide. The flow of water during the low tide is much greater than that of the high tide. For example, the riverine mangroves produce asymmetrical tidal currents which are stronger at the low tide than at the high tide (Medeiros and Kjerfve 1993). The fast low tide tends to flush out the material from the mangrove swamp area and maintains the depth of creeks. When the area of forest swamp is reduced, the speed of the low tide is reduced, and the creeks get clogged up. This is commonly observed in some Southeast Asian countries where deforestation of mangroves has reduced the navigability of the canals and river mouths (Wolanski et al. 1992).

1.3.9 Trapping & Recycling of Nutrients

Mangrove soil serves as a ‘sink’ for retaining nutrients. This depends on the soil characteristics and water flow patterns of the mangrove habitats. Mangrove soil, algae, microbes, and physical processes absorb large amounts of organic and heavy metal pollutants (Wong et al. 1995). Therefore, mangroves especially *Avicennia marina* are capable of surviving in the areas that are dumped with heavy organic wastes and toxic heavy metals. Ammonium nitrogen is rapidly assimilated by bacteria and benthic algae present in the mangrove soil and hence, export of ammonium nitrogen is largely prevented. The loss of nitrogen and phosphorus is also significantly prevented due to reduced flow of water in the severely damaged mangrove areas, as reported in the North Queensland (Kaly et al. 1997).

Mangrove soil is highly efficient in absorbing and holding heavy metals such as Fe, Zn, Cr, Pb, Cd, Mn, and Cu, thereby preventing the metal pollution in coastal environments. In the mangrove ecosystem, heavy metals are mostly trapped down in the soil, but only $<1\%$ of all these metals are present in mangrove vegetation (Silva et al. 1990). This trend of higher levels of heavy metals in soil than vegetation is due to (1) low availability of metals to the plants from sediments, (2) exclusion of the metals by the mangrove plant itself, and (3) physiological adaptations that prevent accumulation of metals inside the plants. Oxygen exuded by the underground roots promotes the formation of iron plaques that adhere to the root surfaces and prevent the trace metals from entering the root cells. The metals are precipitated in the form of stable metal sulphides under anoxic conditions and the sulphides are buried deep into the mangrove soil. This process decreases the bioavailability of trace metals to the plants from the mangrove soil. Mercury does not form sulphides, and hence it is immobilized in organic complexes in mangrove soil. Disturbances may cause the mangrove soil to lose its metal binding capacity, resulting in the mobilization of metals. The degrading mangroves then shift their site from 'sink' to 'source' of heavy metals (Lacerda 1998; Kathiresan and Bingham 2001).

In addition to retaining nutrients, the mangrove systems also help in recycling of nutrients especially carbon, nitrogen, and sulphur and making the nutrients available in assimilable forms to other organisms. It is noteworthy that mangrove ecosystem is the only biotic system that most efficiently recycles sulphur.

1.3.10 Litter Decomposition & Nutrient Enrichment

Mangroves produce large amounts of litter in the form of falling leaves, branches, and other debris. These litters are subjected to leaching of nutrients and microbial colonization, which produce high levels of dissolved organic matter and the recycling of nutrients both in the mangrove and in adjacent habitats. The nutrients can potentially enrich the coastal sea and, ultimately supporting the fishery resources (Lee et al. 1990; Benner et al. 1990; Chale 1993).

Microbes play a vital role in decomposition of mangrove litter and recycling of nutrients. During early decomposition process, potassium and carbohydrates are quickly leached out in a very short time. Tannins, in contrast, leach out very slowly and the high level of tannin reduces the colonization of bacterial populations in the initial period of decomposition. However, tannins are degraded by fungi which are the earlier colonizers on the mangrove litter. Once the tannins are leached out and fungally decomposed, the bacterial populations rapidly increase (Steinke et al. 1990, 1993; Rajendran 1997; Rajendran and Kathiresan 1999). The N_2-fixing azotobacters are one of the important groups in decomposing litter (Chale 1993; Wafar et al. 1997), and their activities increase the content of protein nitrogen by 2–3 times in the litter after 1 month of decomposition (Fig. 1.7; Rajendran 1997). This protein-rich detritus in turn, attracts shrimp, crabs, and fish.

1.3.11 Supporting Fishes and Wildlife

Mangroves are important for fish production by serving as nursery, feeding, and breeding grounds for crabs, prawns, mollusks, and finfish. The calm waters provide habitat for fishes, while the mangrove aerial roots, tree trunks and forest floor support oysters, snails, barnacles, crabs, and other invertebrates. The muddy or sandy sediments of mangroves are inhabited by a variety of epibenthic, infaunal, and meiofaunal invertebrates. Nearly 80% of the fish catches are directly or indirectly dependent on mangrove and other coastal ecosystems worldwide (Kjerfve and Macintosh 1997; Kathiresan 2000; Kathiresan and Rajendran 2002). The mangroves also support a variety of wildlife such as the Bengal tiger, dolphins, monitor water lizard, estuarine crocodile, deer, sea turtles, monkeys, wild pigs, snakes, fishing cats,

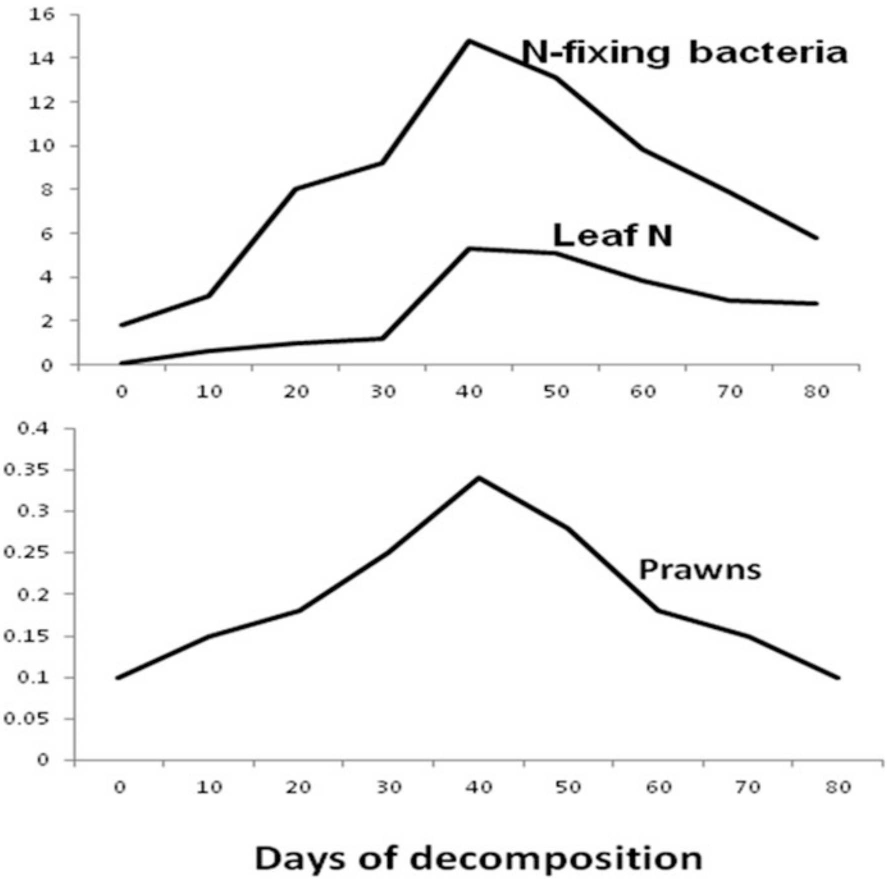

Fig. 1.7 Changes in the nitrogen–fixing azotobacter counts (1×10^4 g^{-1} leaf tissue), the total nitrogen content (% of leaf tissue) and the juvenile prawns (no. $haul^{-1}$) along with decomposing senescent leaves of *Avicennia marina*

insects, and birds. Mangrove leaves, flowers, and fruits are fed in fresh condition by insects, mollusks, crabs, and mammals. Ants protect mangrove trees from insect grazers. A variety of species including bees, bats, and birds such as humming birds, sun-birds, and honey eaters facilitate pollination. Many bird species use mangroves as nesting or roosting grounds, including terrestrial and marine species (Kathiresan and Bingham 2001; Kathiresan and Qasim 2005).

1.3.12 Supporting Coastal Food Web

Mangrove habitats contribute to complex food webs and energy transfers between terrestrial and marine systems (Fig. 1.8). The mangroves produce decomposing

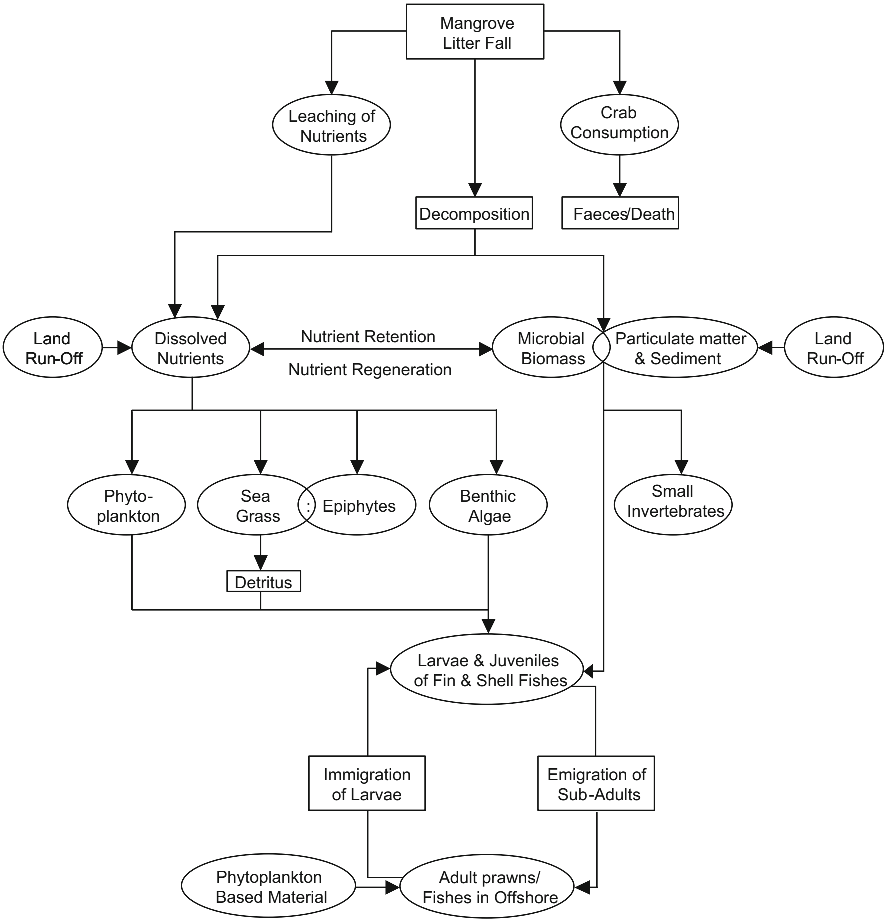

Fig. 1.8 A food web in a mangrove and coastal offshore ecosystems

organic matter, known as 'detritus' which serves as nutritious food to innumerable finfish and shellfish especially juveniles. These detritus–feeding fishes are preyed upon by larger carnivorous organisms. In addition to detritus, the mangrove litter decomposition provides essential nutrients to boost the growth of microorganisms and phytoplankton which are fed by zooplankton and fishes in mangroves and offshore regions (Marshall 1994; Robertson and Alongi 1995; Alongi et al. 1992; Twilley et al. 1992; Hemminga et al. 1995; Alongi 1998).

Mangroves are detritus-based system. The juvenile fishes feed directly on mangrove detritus, small detritivorous invertebrates and on benthic microalgae growing in the mangrove system. The sub-adult fishes migrate from mangroves into sea that is predominant with plankton-based materials, while the juveniles immigrate from sea into the mangrove system that is predominant with detritus-based materials. Thus the life cycle of fishes is completed with the help of mangroves and other coastal systems.

Mangrove plants are the key primary producers, in addition to algae, benthic algae, and phytoplankton in the mangrove forests. These forests also receive considerable quantities of external organic material that are transported from upstream or offshore ecosystems. About 10% of net productivity of mangroves is incorporated within local sediments, while 50–60% is consumed or decomposed, and 30% is exported to offshore regions. The nutrient export also supports productivity in adjacent waters including benthic and pelagic systems of other coastal ecosystems such as seagrasses and coral reefs (Kathiresan and Qasim 2005).

1.3.13 Protecting Other Coastal Systems

Mangroves provide protection to other coastal systems such as coral reefs, seagrasses, and seaweeds. The mangroves are preventing the coastal soil erosion, supplying the clean water after trapping soil particles, and providing the nutrient-rich water through litter decomposition. However, when the mangroves are removed, the loose sediment makes water turbid and not allowing required light for primary production, thereby destroying the associated systems (Fig. 1.9).

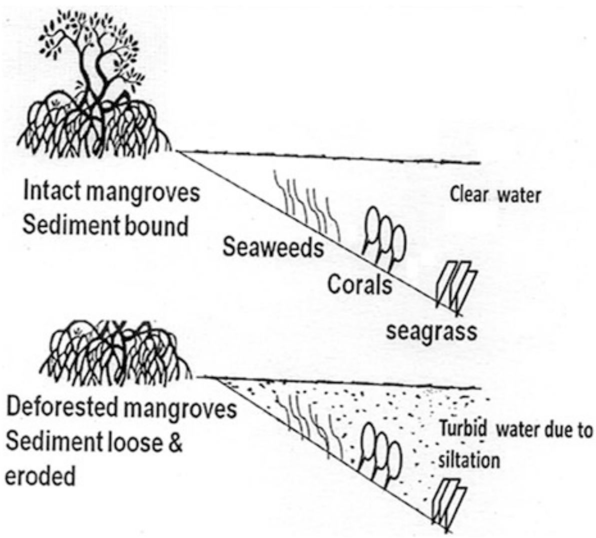

Fig. 1.9 Influence of intact or deforested mangroves on seaweed, coral and seagrass ecosystems

1.4 Uses of Mangroves

Mangroves are of great economic value, providing the ecosystem services worth of at least 1.6 billion US dollars per year, and supporting the coastal livelihoods worldwide (Costanza et al. 1997). Ecosystem economic value is estimated at 91000 US dollars for one hectare of mangrove forest, which is greater than other marine ecosystems: seagrasses, deep sea, coastal plankton, and tidal marsh (Macreadie et al. 2019). The mangroves are known to support over 70 direct human activities, ranging from fuel-wood collection to fisheries (Dixon 1989; Lucy 2006). The economic value is placed in a range of 2000–9990 US dollars per hectare per year, and this is much greater than that of coral reefs, continental shelves or the open sea (Costanza et al. 1997; Spalding et al. 2010). One hectare of mangroves is estimated to store 794 tons of CO_2 equivalent for the carbon credit value of Rs. 168 per ton of CO_2 storage, to protect 243 people from flood, to support the commercial fish stock of 25.3 million individuals, to yield the annual fish catch of 5.7 tons with economic gain of Rs. 4.3 lakh (Kathiresan and Rajendran 2002; Thomas and Mark 2018).

1.4.1 Firewood and Wood Products

Mangrove twigs are used for making charcoal and firewood, due to high calorific value. Charcoal is an energy product largely derived from *Rhizophora* species in Thailand, Malaysia, Vietnam, and Indonesia. One ton of mangrove firewood is equivalent to 5 tons of coal, and it burns producing high heat without generating smoke. In Thailand, about 90% of the felled timber is used for charcoal production. From Thailand and Indonesia, mangrove charcoal is exported to Singapore, Malaysia, Hong Kong, and other Asian countries (Kathiresan 2015).

Mangrove wood is termite-resistant and durable due to its high content of tannin, and hence the mangroves are used as timber. Pneumatophores are used to make bottle stoppers and floats. Mangrove palm (*Nypa*) leaves are used to thatch roofs, mats, and baskets (Fig. 1.10). Its sap of young inflorescence is used for sugar production, alcohol distillation, and vinegar production. Its soft endosperm of fruits is edible and widely used in Thailand, Indonesia, and Philippines.

Mangrove wood chips are a priced commodity for export in Indonesia and East Malaysia. The stalks and fibres are processed into cellulose, paper, and artificial silk (rayon) and supplied from Indonesia to Japan and Taiwan, for cellulose industrial use. Japan has established paper mills and chipboard factories in Kalmantan and Sumatra of Indonesia (Kathiresan 2015).

Tannin is extracted from the bark of mangroves belonging to the family Rhizophoraceae and is used for tanning leather and fishing nets in India, Malaysia, and Pakistan. Extracts of *Bruguiera parviflora*, *B. gymnorrhiza, Rhizophora apiculata, R. mucronata,* and *Ceriops tagal* are used for tanning fishing nets and fish traps in northern Australia.